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PROTOTYPE OF A SEMI-AUTOMATED MACHINE FOR GLASS BOTTLES CUTTING OF EASY ACCESS

por

Jovheiry Christopher García Guerrero

The present thesis is dedicated to all my family who supported and motivated me all these years to continuing my studies, to my professors who help me with valuable advices and feedbacks, and to all people who are looking to improve the ecosystem, for a better tomorrow.

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Resumen

La contaminación del agua pone en peligro al medio ambiente circundante y los seres vivos. En México ya se han presentado casos de muertes masivas de peces, afectando el alrededor de los ambientes y personas aledañas cuya actividad económica depende del cuerpo de agua. En 2020, el 63,67% del agua superficial de México se consideró como contaminada. Para prevenir estas situaciones, se propuso un prototipo de un Sistema de Monitoreo de la Calidad del Agua (WQMS, del Inglés *Water Quality Monitoring System*) basado en un Vehículo de Superficie No Tripulado (USV, del Inglés *Unmanned Surface Vehicle*). El sistema fue basado en un barco tipo catamarán y diseñado para monitorear cuerpos de agua dulce, similares a lagos y presas. El WQMS utilizó tres parámetros de vital importancia para el desarrollo y la supervivencia de la vida acuática (pH, oxígeno disuelto y temperatura). Se utilizó el sistema para comparar el comportamiento de los sensores cuando el USV se encuentra en reposo o en movimiento, además de observar el consumo energético del sistema, con el fin de comprobar si el monitoreo continuo permite reducir el tiempo de monitoreo mientras las mediciones mantienen una precisión similar, en comparación al monitoreo punto a punto. Como resultado, se observó que en el monitoreo continuo las mediciones si se ven afectadas por el movimiento del USV, sin embargo, se observa que las mediciones para el sensor de pH permanecen dentro de un mismo rango del valor en reposo, de $0.2[pH]$, mientras que en el caso del oxígeno disuelto aumentan los valores durante un tiempo (debido al tiempo de respuesta del sensor) hasta alcanzar un valor casi constante. En el caso del sensor de temperatura, también se vio afectado, sin embargo, su efecto es muy pequeño. Al comparar las mediciones y el consumo energético con un caso ideal, se verifica que el monitoreo continuo mantiene unas mediciones similares y un tiempo de monitoreo menor con respecto al monitoreo punto a punto.

Palabras clave: Sistema de Monitoreo de la Calidad del Agua (WQMS); Vehiculo de Superficie no Tripulado (USV); Calidad del Agua (WQ); Monitoreo Continuo; Monitoreo Punto a Punto;

Abstract

Water pollution endangers the surrounding environment of freshwater reservoirs. In fact, in Mexico there have already been cases of massive fish deaths, affecting the surrounding environments and people whose economic activity depends on the body of water. In 2020, 63.67% of Mexico's water bodies were considered contaminated. To prevent and avoid these situations, a prototype of Water Quality Monitoring System (WQMS) based on an Unmanned Surface Vehicle (USV) was proposed. The WQMS was based on a catamaran-type boat and designed to monitor freshwater bodies, similar to lakes and dams. The WQMS monitors three parameters of vital importance for the development and survival of aquatic life (pH, dissolved oxygen and temperature). This system was used to compare the behavior of the sensors when the USV is at rest or in motion, and to observe the energy consumption, in order to verify if continuous monitoring allows reducing the monitoring time while the measurements maintain a similar precision in point-to-point monitoring. As a result, it was observed that in continuous monitoring measurements are affected by the movement of the USV, however, it is observed that the measurements for the pH sensor remain within the same range of values (the value in rest to the same minus $0.2[pH]$), while in the case of dissolved oxygen the values increase for a while (due to the response time of the sensor) until reaching an almost constant value. In the case of the temperature sensor, it was also affected, however, this effect is very small. By comparing the measurements and energy consumption with an ideal case, it is verified that continuous monitoring maintains similar measurements and shorter monitoring time than point-to-point monitoring.

Keywords: Water Quality Monitoring System (WQMS); Unmanned Surface Vehicle (USV); Water Quality (WQ); Continuous Monitoring; Point-to-Point Monitoring;

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CHAPTER 1

Introduction

Water protection is so crucial due to its stochastic availability. Many civilizations flourished in ancient times thanks to water and disappeared due to poor quality or scarcity. In recent years, water contamination has been so high because of the continuous development and growth of industry and an increase in population. An example of high pollution of superficial water was the Thames River near London, devoid of dissolved oxygen due to the high pollution level [1].

Water quality has many definitions, which depend on many variables and the target activity. Nowadays, most freshwater bodies are used for recreational purposes, which endangers the water quality due to human activity. The World Health Organization (WHO) has published a book with guidelines on water quality in costal and freshwater. In this, water quality is focused on indicators of fecal pollution, harmful algae blooms, microbial hazards, and some specific chemicals [2]. Also, it talks about recommendations for monitoring, but implementing this process entails many points, which can only be implemented by people specialized in this topic.

Implementing a Water Quality Monitoring System (WQMS) was born to solve the problems that previously involved measuring water quality. Initially, Water Quality Monitoring (WQM) was a process that requires:

- visit the monitoring site
- obtain water samples
- store the samples
- transport the samples
- perform laboratory test

Some common problems related to these steps are the contamination or alteration of water samples due to inadequate storage or transport and some chemical reactions and processes (due to the change in temperature during transport), which caused an error in the measurement of the parameters. In addition, a lot of time was required to complete the entire quality monitoring process (from the arrival at the measurement site and the water samples obtained to the laboratory where tests are performed). It represents the principal aspect of determining the frequency of monitoring water quality, which also does not allow for the detection of some problems or events negatively affecting the ecosystem.

Part of the problem related to the transporting of samples was solved when specialized devices that allowed measuring the parameters of interest in the same monitoring place were manufactured, such is the case of the system developed in [3–5] (other parameters still require to be obtained with laboratory tests). However, it did not solve the problem related to sample transporting. As a solution, WQMS were proposed.

WQMS are automated systems that measure one or more water parameters to know the state of health of a body of water or the state of the water itself for use in a specific activity. In the case of water quality for aquatic life, it usually measures parameters affecting the survival and development of species, such as Dissolved Oxygen (DO) and pH, and detects related events. A practical case of monitoring in aquaculture is introduced in [6]. Initially, WQMS were systems that focused on measuring the parameters of interest at a single point. WQMS were able to use a wireless connection to monitor the results obtained. Nevertheless, this is convenient for monitoring water in small areas, such as water tanks [7]. Given the necessity to carry out the WQM in more extensive areas to detect events/situations that affect water and endanger activities or those who depend on water, WQMS based on wireless networks, also known as Wireless Sensors Networks (WSN), were created to link different nodes containing some sensors required for the WQM. WSN-based WQMS allowed monitoring along rivers, canals, etc. [8]. These could even monitor large areas by installing different nodes around them, similar to the developed systems in [9–12]. These systems also have a degree of complexity, and their implementation requires considering certain aspects to obtain the correct data [13]. Then, several studies have been developed and focused on the analysis of these problems and the improvement of measurement systems [14]. One aspect to highlight is that WSN-based WQMS are often associated with IoT (Internet of Things) solutions. However, implementing these types of systems requires a substantial monetary investment. The greater the number of nodes and parameters to be measured, the greater the implementation cost (without considering maintenance and other aspects).

As a solution to this situation (and with new objectives), different WQMS were proposed with the characteristic that sensors were installed in a vehicle with the ability to move on water. Whether this vehicle could be controlled manually or automatically, this system reduced the cost of implementing WSN-based WQMS and enabled monitoring of larger areas. However, this system entails certain disadvantages, such as the total time required to perform the WQM in all the water bodies and the control of the system by a trained person (if the vehicle is not automated), among other problems. The interest in this type of system is such that research has been carried out on the requirements of these systems for their autonomous operation [15]. This type of vehicle is commonly known as an Unmanned Surface Vehicle (USV). Some WQMS with the monitoring system installed inside USV are in [16; 17].

1.1 Problem description

By analyzing the 2020 superficial WQ report from Mexico, 1267 superficial water bodies (36.37%) had no contamination (green indicator), 1135 had some level of contamination (yellow indicator), and 1091 had a high level of contamination (red indicator) [18]. In the case of Querétaro state, Table 1.1 presents the contamination level in superficial water bodies.

Table 1.1: The situation of superficial WQ in Querétaro de Arteaga, 2020.

Superficial water type	Level of contamination			Total
	Green	Yellow	Red	
Rivers	3	5	18	26
Stream	-	-	3	3
Drain	-	-	1	1
Discharge	-	1	4	5
Dam	1	-	7	8
Total	4	6	33	43
Total percentage	9.30	13.95	76.74	100

Table 1.1 shows that only 9.3% of the superficial water bodies had a green indicator. The pollution jeopardizes the surrounding flora and fauna. There have been many cases in Mexico of massive death of fish due to polluted water bodies (mainly in lakes and dams). A solution that enables the opportunity to prevent and avoid these events is to develop a WQMS focused on similar freshwater bodies to lakes, ponds, and dams. Then, the best solution is a system based on USV.

USV-based WQMS represents a challenge due to the requirements for its operation, either autonomously or controlled remotely by a person. In this way, various systems have been developed with different approaches, such as low-cost USV [19], obstacle detection [20], hybrid USV [21], or the ability to collect objects from the water surface [22]. Additionally, studies have been carried out that allow obtaining a model to predict specific parameters to avoid disasters, as in [23], where the DO prediction is made. In general, the WQMS has been improving its operation and characteristics to offer various solutions according to specific problems, and they have been combined with different techniques and methods to improve the measurement and monitoring of water quality to prevent undesirable situations.

Despite these systems being studied, developed, and improved worldwide, it seems different in Mexico due to the lack of documentation showing different WQMS developed or implemented in the country. Besides, considering that there have been cases of massive fish deaths (carrying both ecological and economic risk) in freshwater bodies where no monitoring is carried out, it is necessary to develop and implement similar systems to:

- Carry out monitoring on the same freshwater body for a long period. It allows one to carry out the monitoring process more frequently, detect events that endanger water quality (to carry out corrective actions), and observe the parameter trend (to perform preventive actions).
- Obtain highly accurate parameter measurements.
- Depending on the body of water, have a suitable type and data transmission distance.
- Reduce implementation cost.

All this is done to avoid similar situations by having systems that suit the needs. Some problems that must be solved when developing a USV-based WQMS are related to:

- Implement the appropriate algorithms for proper functioning autonomously and, if necessary, manually.
- Select the type of wireless transmission that best suits the needs of the WQMS and, above all, which provides a transmission distance according to the dimensions of the monitoring location.
- Implement sensors or measurement instruments that adequately read parameters in the surrounding environment.
- Implement sensors, modules, and other components to monitor the performance or state of the USV.
- Use a controller unit with the features to execute all algorithms developed adequately.
- Develop a system/application to control and obtain data remotely.
- Reduce the time to perform all the WQM processes.
- Avoid unnecessary energy consumption due to battery limitation.

1.2 Justification

All USV-based WQMS found in the literature review were developed in other countries, despite these systems representing an excellent tool for water protection. According to the analysis of [18], the situation of superficial water bodies in Mexico is deplorable. Only 36.37% of the total are not contaminated. Also, the parameters used in [18] do not include pH, although it represents one of the essential parameters for aquatic life development. Then, it is necessary to develop a system for WQM with the most critical parameters required for aquatic life survival and accomplish the Mexican norms related to water quality.

The system proposed must consider a low-cost option. Usually, WQMS analyzes one spot of water only, which is convenient for short water reservoirs but not for wider ones. Then, a better option is to implement a WSN-based WQMS with multiple sensor nodes, which reduces time and constant in-situ monitoring. But these systems also have a high cost of implementation (which varies according to the number of nodes and the parameters). The best option for monitoring freshwater reservoirs, like dams and lakes, is a USV-based WQMS, which can monitor more expansive areas and are less expensive than WSN-based. Also, these affect the time to complete the monitoring process.

Due to USV-based WQMS usually requires monitoring many spots in the freshwater reservoir (at least once per spot and each at a time), and considering that monitoring each point takes several minutes (since USV arrives at the desired place, activates sensors, performs parameters measuring, deactivates sensors and go to the next desired spot), the time to complete the WQM process increases. Then, it is necessary to develop algorithms that can reduce the time for monitoring.

One of the most used monitoring processes in all the USV-based WQMS developed is the point-to-point monitoring. It means monitoring only some specific and limited number of spots inside a freshwater body (usually, the user specifies the exact number of points for monitoring). Each time sensors are turned on, they require a few minutes to obtain a reliable measure.

Something to take into account is the battery installed in the USV. Due to its limited capacity, the battery must have enough energy to complete at least once the process is required. An easy way to solve this is to acquire a battery with high energy capacity, but it increases the price and weight of the project. In most cases, the vehicle is designed to accomplish some requirements, among which is the weight that the project moves. When the battery discharges, the USV is affected to the point where it can stop moving. Then, it is necessary to find a way to reduce energy consumption without modifying the vehicle characteristics.

1.3 Hypothesis

A USV-based WQMS that keeps the sensors on and moving during the monitoring process reduces power consumption compared to a similar system that stops its progress to performing the monitoring process, maintaining similar values in the measurements.

1.4 Objectives

1.4.1 General objective

Obtain the energy consumption of a USV-based WQMS by developing a prototype that includes sensors for temperature, pH, dissolved oxygen (DO), and depth to compare the energy consumption for the monitoring types point-to-point and continuous and see which represents the best option for its implementation.

1.4.2 Specific objectives

1. Design and implement a prototype of a WQMS based on a USV.
2. Develop control algorithms for point-to-point and continuous monitoring.
3. Implement the prototype in different controlled and practical environments.

4. Obtain the energy consumption of the prototype for each monitoring process implemented.
5. Compare energy consumption and time used in each monitoring process implemented.

The thesis is presented in 6 chapters: Chapter 1 introduces the problem to solve, the justification, hypothesis, and objectives for the thesis; Chapter 2 presents the stat-of-art for WQMS based on USV; Chapter 3 contains all the theoretical framework that was used/proposed; Chapter 4 introduces the methodology for prototype development and experimentation; Chapter 5 presents all results from multiple tests and its analyses; and Chapter 6 concludes about the project developed.

CHAPTER 2

Background

This section compiles the results from a systematic review focused on documents related to "Water Quality," which have the keywords "Unmanned Surface Vehicle" or its acronym "USV."

2.1 State of art

The principal database used in the systematic review was Scopus. In this case, due to the acceptance process, the review only accepted 19 of 39 documents. Also, ResearchGate was used to complement the review. In this case, only 10 articles were accepted. Table 2.1 introduces a summary of the WQMS based on USV, Table 2.2 presents the main characteristics of these, and Tables 2.3 and 2.4 are about the devices, systems, apps, and functions used for remote control or data acquisition.

Table 2.1: Previous related works.

Ref.	**Description**
[16]	The WQMS was designed for river monitoring.
[15]	The USV is a catamaran-based. The WQMS also samples water, collects objects and avoids obstacles.
[17]	The WQMS was designed and tested in shallow waters and wetlands.
[19]	The USV is based-on Waterplane single-hull. The WQMS avoids obstacles and streams video. It was tested on Honghu lake.
[24]	The USV is a catamaran-based. It was tested on a pond.
[20]	The USV is a catamaran-based. The system can monitor at different depths. It was tested in a lake with aquaculture zone.

[21]	The WQMS can stream video. It was tested on a river.
[22]	The USV incorporates an edge platform, which reduces the interaction delay between the user and the USV. Also, the USV is a catamaran-based.
[25]	The USV is based on a quadropod-like structure. The WQMS records video with a video camera pointing at the bottom. It was tested on Constance lake.
[26]	The WQMS was designed for monitoring lakes, ponds, rivers and coastal waters. The USV is a catamaran-based.
[27]	The WQMS was tested on Derdanelle lake. The USV is a catamaran-based.
[28]	The WQMS streams video. The USV is a catamaran-based.
[29]	The WQMS was tested on a freshwater reservoir. The USV uses a double-hull design (similar to a catamaran).
[23]	The WQMS was implemented on a pioner boat.
[30]	The WQMS implements a hydrophone and gas sensor with a Raspberry. No design is shown.
[31]	The USV is based on a jeat boat.
[32]	The WQMS was tested on TamSui river.
[33]	The WQMS samples water and streams video. The USV is a catamaran.

Table 2.2: Main characteristics of the WQMS in the review.

Ref.	**Control devices**	**Data communication**	**WQ sensors**	**Others sensors**	**Navigation**
[15]	2 x Arduino Mega 2560	Bluetooth HC-08	pH sensor SEN0161	Vision sensor Pixy CMUcam5	GPS (GY-GPS6MV2)
[16]	-	RF Modem, ¡ 3 KM, 2.4-2.483 GHz	AlgaeChek ultra (Chlorophyll-a), depth sounder	Video camera, LiDar	GPS/IMU, Compass
[17]	Raspberry Pi 3.0 model B SBC, Huzzah ESP8266 board	2.4 GHz Wi-Fi	-	NGC Sensors	GNSS DP0106, IMU Adafruit BNO055

[19]	-	RF modem	Chl-a, turbidity, DO, conductivity, ORP, temperature, salinity, pH	Velocimeter, spectral adquisition system, presion, humidity	GPS, 3 compass, Gyro
[20]	STMF32F103Z, STMF32C8t6	Wi-Fi	TDS, pH, turbidity	-	GPS, MPU9250
[21]	Raspberry Pi	4G-based DTU, LiDar	-	Doppler	GPS, IMU
[22]	Raspberry Pi, MCU STM32, Arduino	Wi-Fi	pH, temperature, turbidity	-	GPS
[23]	Odroid XU4, 2 x Arduino	Wi-Fi	temperature, pressure, humidity	-	Razor 9 DOF IMU, Adafruit GPS
[24]	Beaglebone Blue, Jetson nano	Wi-Fi, 900 MHz RF modem	Adafruit V1 Sensor	-	GPS, 9 DOF IMU
[25]	-	-	Hydrolab MS5 (pH, DO, conductivity, temperature, turbidity)	2 x echo sounders	-
[26]	2 x Arduino UNO	XBee Series 1 radio module, Liberlium SX1272 LoRa	pH, ORP, salinity, DO	Echo sounder y flow sensor	2x GPS
[27]	AtMega32U4	RN2903 LoRa 915 MHz	pH, turbidity, DO, temperature	-	-
[28]	STM32F103ZE	Wi-Fi, Bluetooth, 4G module	pH, TDS, turbidity	Ultrasonic module	WF-NEO-6M GPS, 9 axis sensor
[29]	-	Red 4G	Chl-a, DO, conductivity, potassium ion, pH, temperature, turbidity	-	-
[30]	Raspberry Pi 3	3G/4G	Temperature, conductivity, relative humidity	Gas sensor TGS800, Hydrophone	-
[31]	PCM 3353	-	-	-	-

[32]	-	Wi-Fi	-	-	GPS, compass
[33]	-	-	Temperature	Depth	GPS
[34]	Arduino	Module 5G MH5000-31	Temperature	Humidity, rain, pressure, altitude and wind speed	-
[35]	Raspberry Pi 3 and Arduino Mega 2560	WLAN transmitter	Multi-parameter probe (temperature, pH, DO, turbidity, conductivity, and Colored Dissolved Organic Matter (CDOM))	Bathymeter	GPS, IMU
[36]	-	Cellphone uplink	Salinity, AML Oceanographic multisensor (temperature, DO and pH), SeaBird Scientific multisensor (Chlorophyll-a, Phycocyanin, phycoerythrin, CDOM, turbidity, backscatter and DO)	-	-
[37]	Raspberry Pi	LoRa SX12772 module and Radio Shield Libelium multiprotocol module	Temperature, pH, salinity, turbidity and electrical conductivity	Depth	GPS, IMU
[38]	STM32F10-3ZET6	LoRa	Temperature, pH, turbidity and conductivity	-	GPS, IMU MPU 9250
[39]	Arduino Mega 2560	Telemetry module	-		U-Blox GPS, MEMS 3-axis magnetometer

[40]	ATMEGA2560-16U	Satellite communication with RockBLOCK module and RFM95 breakout module	Temperature, pH, conductivity and DO	-	IMU ICM-20948, GPS
[41]	-	4G Wi-Fi router	Water sensors (not specified)	LiDar, Radar	GNSS, IMU
[42]	-	AIS transceiver, TightVNC version 4.8.8	-	Sonar SIMRAD EK80	GPS
[43]	2 x Adafruit Pro Trinkets	2 x Bluetooth	Temperature, pH, turbidity	Current and voltage sensor	GPS

Table 2.3: Software/hardware implemented for USV controlling: remote control options.

Remote control option	Ref.
Application	[15; 21–23; 25; 28; 30; 37; 38; 42; 43]
Physical control station	[16; 17; 19; 25; 29; 31–33; 35; 39]
Cloud service/platform	[20; 22; 26; 27; 34; 36; 40]

Table 2.4: Software/hardware implemented for USV controlling: main functions.

Main functions	Ref.
Data management	[15; 16; 19; 22; 23; 26–28; 30; 32; 34–40; 42; 43]
USV control	[15; 17; 19; 21–23; 25; 26; 28; 31; 33; 40; 42; 43]
Route management	[16; 19; 29; 31]

All the articles cited in Table 2.1 present a USV for monitoring the water and use point.to-point monitoring to reduce energy consumption because of the limited power supply inside the USV. It causes sensors to turn on every measurement spot, which causes waiting some minutes to obtain a reliable measurement and increases the total time to complete the monitoring process. Reducing the time for monitoring represents an improvement area. Sensing while the USV is moving minimizes the time to complete the monitoring process. Also, it may increase energy consumption. This research analyzes energy consumption and if measurements are altered by comparing both cases, point-to-point or continuous (while moving) monitoring.

CHAPTER 3

Theoretical framework

3.1 Controllers

There are many types of controllers in the world of automation and control of processes. In the case of control loops, the most common and best known is the Proportional-Integral-Derivative (PID) controller. Based on [44], (3.1) represents a PID controller:

$$u(t) = k_p e(t) + k_d \frac{de(t)}{dt} + k_i \int_0^t e(r)dr, \tag{3.1}$$

where:

- k_p is the proportional gain,
- k_i is the integral gain,
- k_d is the derivative gain,
- $e(t)$ is the error,
- $u(t)$ is the control effort.

If the k_d gain is 0, the controller is considered a Proportional-Integral (PI) Controller. If the k_i is 0, the controller is considered Proportional-Derivative (PD). By using the Laplace Transform, the PID controller is represented in the frequency domain as:

$$U(s) = k_p E(s) + k_i E(s) + \frac{k_d}{E(s)}. \tag{3.2}$$

The form of (3.2) is a good option for implementing into a microcontroller. By using (3.2), the controllers implemented in this project are developed. Each controller requires variables to obtain the error value and calculate the PID controller. Then, the following sections introduce the variables used for each controller implemented.

3.1.1 Advance Process

The advance process is integrated by two controllers, a Lead Angle Controller (LAC) and a Forward Velocity Controller (FVC). The LAC is required to modify the forward direction for a correct forward trajectory. Figure 3.1 shows some examples with the points of interest, vectors, and angles related to the advance process.

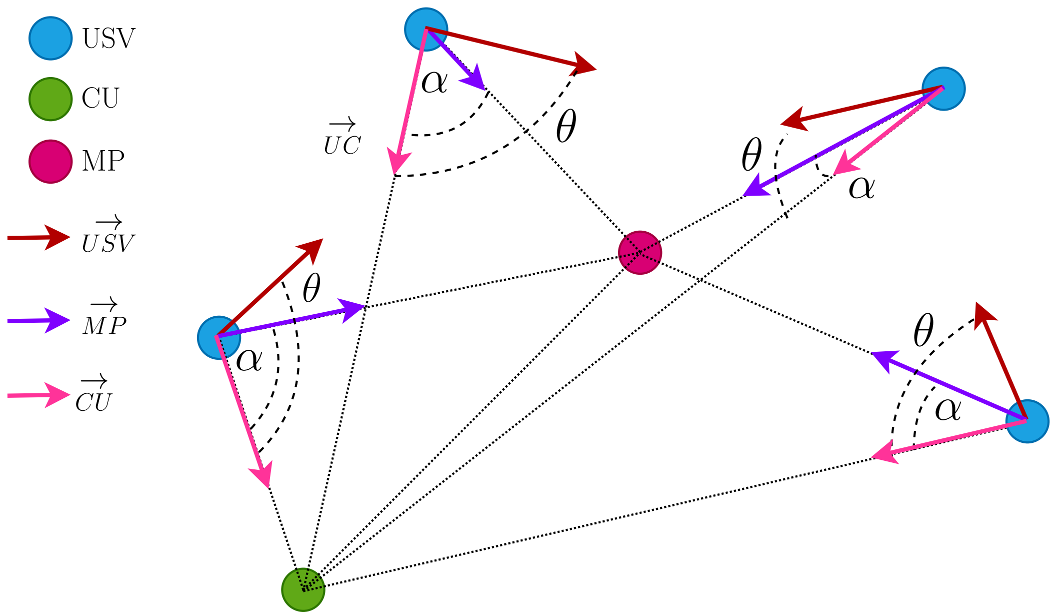

Figure 3.1: Strategy for lead angle controller.

The variables in Figure 3.1 are:

- $\overrightarrow{CU}$ is the vector from USV to Central Unit (CU),
- $\overrightarrow{USV}$ is the vector that represents the forward direction of the USV,
- $\overrightarrow{MP}$ is the vector from USV to MP (Monitoring Point),
- θ is obtained between vectors $\overrightarrow{USV}$ and $\overrightarrow{CU}$,
- α is obtained between vectors $\overrightarrow{MP}$ and $\overrightarrow{CU}$.

By using the values of angles, θ and α, and the coordinates of the USV and MP, the next strategy is proposed:

	$X_{USV} < X_{MP}$	$X_{USV} > X_{MP}$
$\theta > \alpha$	Forward with right turn	Forward with left turn
$\alpha > \theta$	Forward with left turn	Forward with right turn

Table 3.1: Forward direction strategy.

Next equations are used for angles obtaining:

$$\theta = \cos^{-1}\left(\frac{\overrightarrow{USV} \cdot \overrightarrow{CU}}{|\overrightarrow{USV}||\overrightarrow{CU}|}\right) \tag{3.3}$$

$$\alpha = \cos^{-1}\left(\frac{\overrightarrow{MP} \cdot \overrightarrow{CU}}{|\overrightarrow{MP}||\overrightarrow{CU}|}\right) \tag{3.4}$$

The controller-loop proposed for LAC is introduced in Figure 3.2:

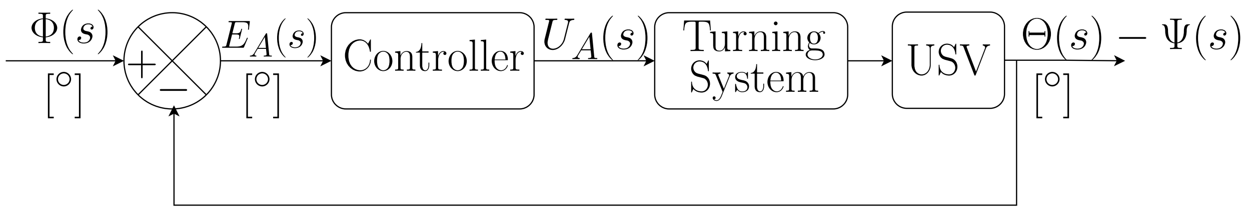

Figure 3.2: Blocks diagram proposed for lead angle controller.

where:

- $\Theta(s)$ is the angle between $\overrightarrow{USV}$ and $\overrightarrow{CU}$,
- $\Psi(s)$ is the angle between $\overrightarrow{MP}$ and $\overrightarrow{CU}$,
- $E_A(s)$ is the error,
- $U_A(s)$ is the control effort.

But LAC only controls the forward direction. The FVC is required to vary the forward velocity to ensure it is at the measurement point. The FVC needs the length between the USV and MP to achieve this. It is represented as $l_{USV \to MP}$ and calculated with the next equation:

$$l_{USV \to MP} = \sqrt{(X_{MP} - X_{USV})^2 + (Y_{MP} - Y_{USV})^2} \tag{3.5}$$

where (X_{MP}, Y_{MP}) represent the coordinates (x, y) of the MP and (X_{USV}, Y_{USV}) the coordinates (x, y) of the USV. Figure 3.3 introduces the velocity controller.

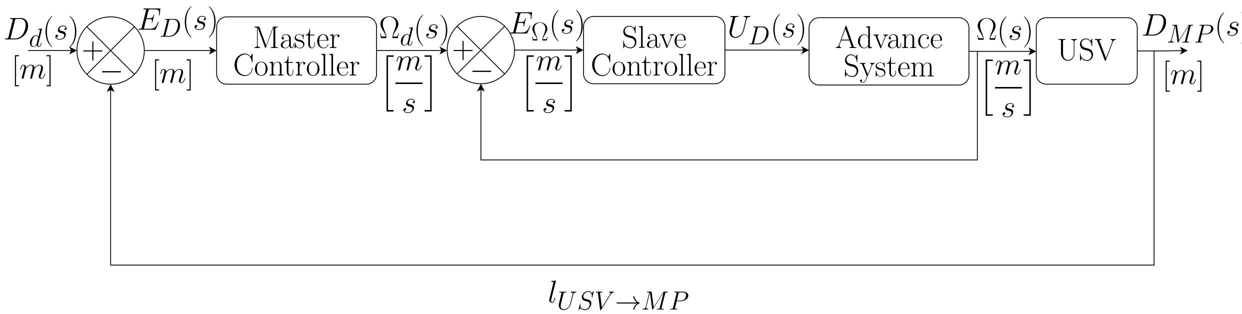

Figure 3.3: Blocks diagram proposed for forward velocity controller.

where:

- $D_d(s)$ is the desired distance between USV and MP, which is equal to $l_{USV \to MP}$,
- $D_{MP}(s)$ is the distance between USV and MP,
- $E_D(s)$ is the error of the master loop,
- $\Omega_d(s)$ is the master control effort,
- $E_\Omega(s)$ is the error of the slave loop,
- $U_D(s)$ is the slave control effort,
- $\Omega(s)$ is the velocity of USV.

3.1.2 Principle of Archimedes

The principle of Archimedes says the buoyant force acting on a body immersed in a fluid is equal to the weight of the fluid displaced by the body and acts upward through the centroid of the displaced volume. Based on [45], (3.6) represents the buoyant force:

$$F_B = W, \tag{3.6}$$

where:

- F_B is the buoyant force,
- W is the weight displaced.

In the case of W, it is expressed with:

$$W = \rho_f g V_{sum}, \tag{3.7}$$

where:

- ρ_f is the fluid density,
- g is the gravity,
- V_{sum} is the volume submerged in the fluid.

If the weight of the entire body is equal or less to the buoyant force F_B, then the body floats. F_B is the weight of the fluid whose volume is equal to that of the submerged part of the submerged body. By considering $\rho_{\text{water}} = 997[\frac{kg}{m^3}]$ and $g = 9.8[\frac{m}{s^2}]$, the maximum weight that a submerged body can stand. Only V_{sum} must be calculated to obtain W. The V_{sum} in this project is calculated by considering the total volume of the buoyant elements, which have cylinder form. By using (3.7):

$$W = 997\left[\frac{kg}{m^3}\right] \times 9.8\left[\frac{m}{s^2}\right] \times (1[m] * \pi * r^2[m^2]), \tag{3.8}$$

the only parameter left is r. In this case, a cylinder of 5 inches ($12.7[cm]$) is used as example for the buoyant elements (in meters, r is equal to $0.127[m]$). Then:

$$W = 997\left[\frac{kg}{m^3}\right] \times 9.8\left[\frac{m}{s^2}\right] \times (0.60[m] * \pi * 0.127^2[m^2]) = 0.016129\left[\frac{kg * m}{s^2}\right] \tag{3.9}$$

But the previous result is in $\left[\frac{kg*m}{s^2}\right]$ (equivalent to Newtons $[N]$). Next, the result is divided by g to obtain the kilograms the buoyant elements can support. As a result, the buoyant elements can support $50.518[kg]$ (mass).

CHAPTER 4

Methodology

This section introduces the recommended steps to develop the project.

4.1 Prototype development

As a first introduction to the proposed WQMS, Figure 4.1 shows a diagram of the prototype:

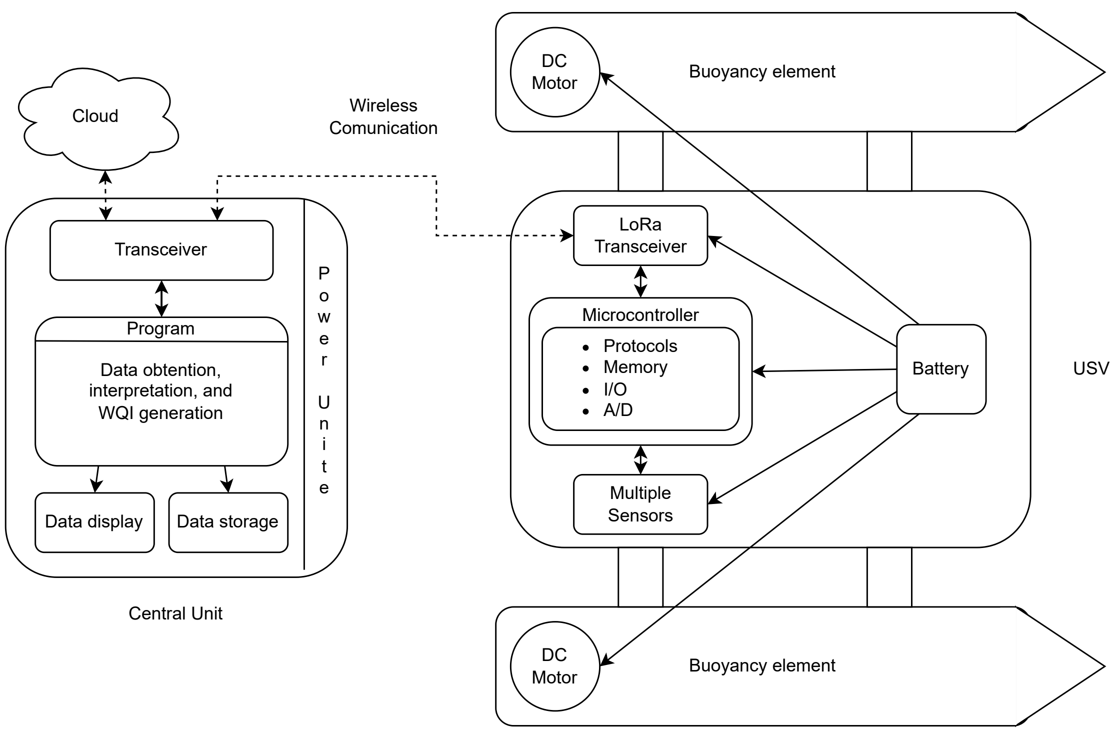

Figure 4.1: Architecture proposed for the WQMS.

and Figure 4.2 presents the structure proposed for the prototype:

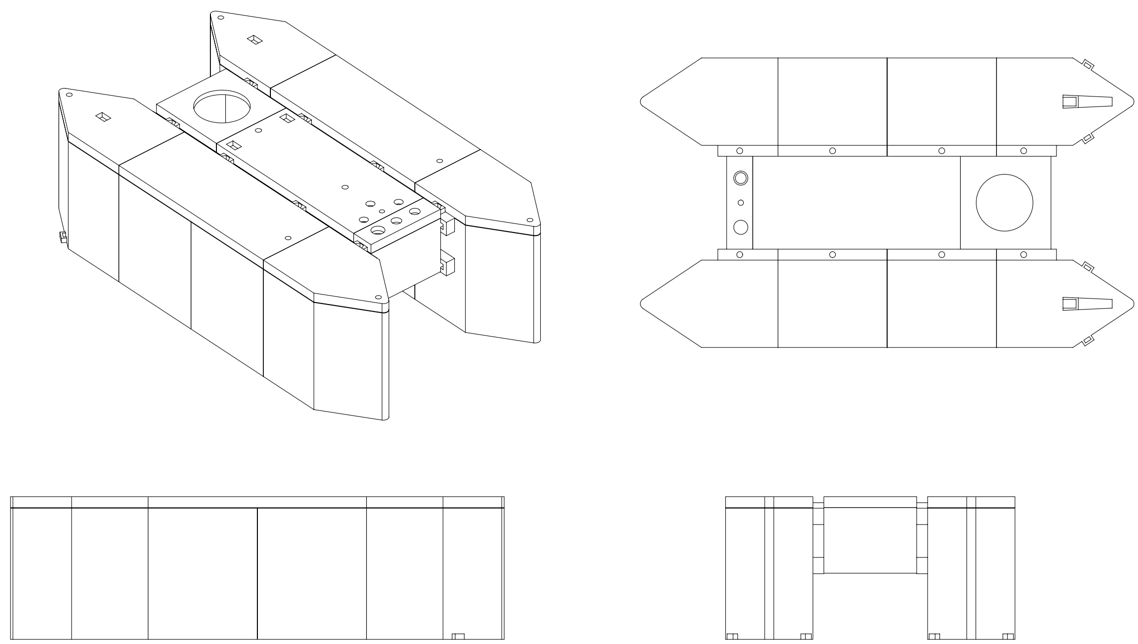

Figure 4.2: Structure proposed for the WQMS.

According to Figure 4.1, the system implements two units. The first unit is the USV, which obtains the parameter values; the second is the Central Unit (CU), which receives the data from the USV for analysis, storage, and display.

The first step in developing the prototype is calibrating and testing the sensors. It requires programming the STM32F4110 to receive sensor data and transmit it to a terminal for its visualization. Then, the microcontroller requires communication with the LoRa module (as an alternative, in this first calibration test, serial communication with a computer is helpful). Figure 4.3 introduces the connection diagram for the USV.

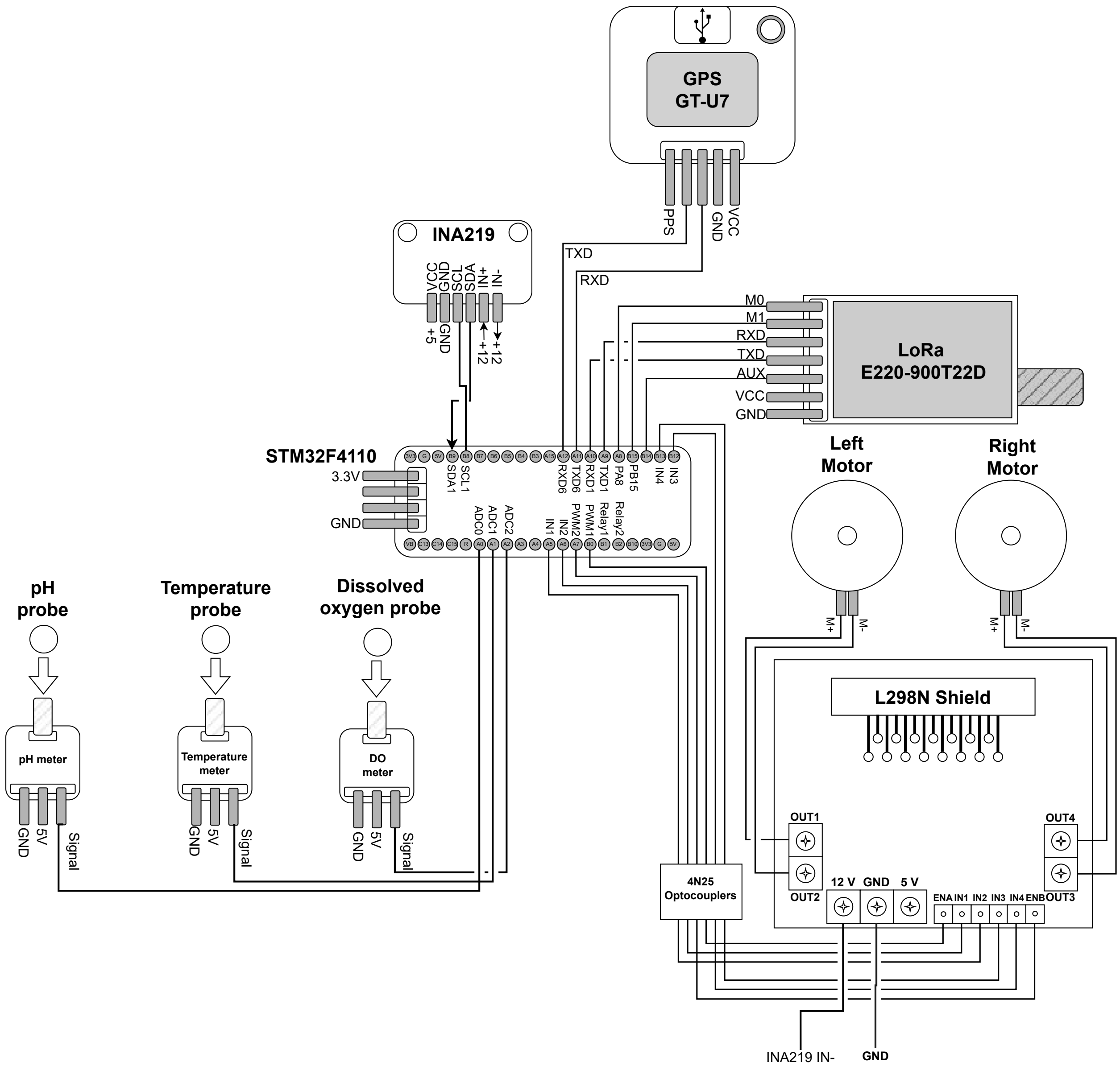

Figure 4.3: USV connection diagram proposed.

The next step is to design the PCB and establish its dimensions. It is recommendable before making the USV structure. The total weight is required once all components, sensors, and other materials are acquired. By using (3.6) and (3.7), the USV weight allows approximating the submerged volume. If the buoyant force equals the USV weight, then the USV floats. A good recommendation is to consider a greater weight than expected. It enables the implementation of more devices, sensors, or elements inside USV for future work and avoids sinking situations.

4.1.1 Materials

This section summarizes the material related with the development of the project.

LoRa communication E220-900T22D

The most common and used wireless communications are systems based on Wi-Fi and Bluetooth technology. The problems with these are related to transmission range and energy consumption. A new wireless communication technology, known as LoRa communication, was developed as a solution. This new technology allows a wide data transmission range and low energy consumption. The LoRa communication module used in this project is the E220-900T22D from Ebyte.

The features for E220-900T22D module are:

- Supports of Air wake-up, an ultra-low power consumption function.
- Transmission distance of5$[km]$.
- Data transmission rate of 2.4 to 62.5$[Kbps]$ and communication level of 3.3$[V]$.
- Power supply of 3.3 to 5.5 $[V]$.
- UART serial port channel.

Figure 4.4 displays its pinout.

Figure 4.4: E220-900T22D pinout.

The pins M0 and M1 are used to decide one of the 4 working modes:

- Mode 0 - Transmission (M0=0, M1=0): It serves to input data through the serial port and starts the wireless transmission. The receiving function is turned on, and after receiving data, it will output through the serial port.
- Mode 1 - WOR transmitting (M0=1, M1=1): The receiving function is the same as the Mode 0. In the case of the transmitting function, when defined as the transmitting party, a preamble is automatically added before transmitting.
- Mode 2 - WOR receiving (M0=0, M1=1): The transmission is turned off, and the receiving function is the same as Mode 1.
- Mode 3 - Deep sleep (configuration) (M0=1, M1=0): The module cannot transmit or receive wireless data. This mode is used for setting some configuration with the supported commands (set register, read register, and set temporary register).

The pin AUX is used to indicate the status of the module. An example is when the module changes from Mode 3 to others. In this case, the AUX pin will remain slow during the configuration process. After the changes, its output is high.

The LoRa module requires configuring some parameters to establish communication. These parameters are:

- Broadcasting address: It is a hexadecimal number with the format *0xFFFF*.
- Monitor address: It has the same format as the broadcasting address, *0xFFFF*.
- Channel: In this case, the format is also hexadecimal but composed of two numbers, *0xFF*.

GPS module GT-U7

The GT-U7 module is a stand-alone GPS receiver. It is characterized by its compact architecture, power, and memory options, which makes it suitable for battery-operated mobile devices.

Some main characteristics of the GT-u7 module are:

- The Time-for-First-Fix (TTFF) in hot-start is under 1 second.
- The GPS has an accuracy of $2.5[m]$.
- It has a configurable UART interface for serial communication. Also, the module has a 2.0 FS USB as an alternative.

Also, the module has three operating modes:

- Maximum performance mode: During a cold start, a receiver continuously deploys the acquisition engine to search for all satellites. Once it has a position fix or (has pre-position information available), the acquisition engine continues searching for all visible satellites that are not being tracked.
- Eco mode: During the cold start, a receiver works precisely as in the previous mode. Once the position can be calculated and enough satellites are being tracked, the acquisition engine is powered off. The tracking engine continuously tracks acquired satellites and acquires other available or emerging satellites.
- Power save mode: It reduces power consumption by selectively switching parts of the receiver on and off.

The GT-U7 module has only 5 pins (VCC, GND, TXD, RXD, and PPS).

IMU module MPU 9250

The MPU-9250 is a 9-axis Motion Tracking device. It has a 3-axis gyroscope, a 3-axis accelerometer, and a 3-axis magnetometer. Figure 4.5 presents the MPU 9250.

Figure 4.5: IMU module MPU 9250.

The main features of MPU 9250 are:

- Communication via I^2C at $400[kHz]$ or SPI at $1[MHz]$
- Supply voltage of 2.4-3.6 $[V]$.
- Gyroscope ADC word length of 16-bit.
- Accelerometer ADC word length of 16-bit.
- Magnetometer ADC word length of 14-bit.

Sensors

The present project proposes 3 sensors for parameters related to WQ (temperature, DO, and pH). Table 4.1 introduces the main characteristics of each sensor:

Table 4.1: Main characteristics of sensors.

Hardware	Model	Characteristics
pH sensor	Atlas Scientific pH probe and Gravity™ Analog pH Sensor	Capacity for long time submerged. Range of meter: 0 - 14. Power supply: 3.3 - 5 $[V]$.
DO sensor	Atlas Scientific DO probe and Gravity™ Analog Dissolved Oxygen Meter	Capacity for long time submerged. Range of meter: 0 - 100% saturation. Power supply: 3.3 - 5 $[V]$.
Temperature sensor	Temperature probe and Gravity™ Analog Temperature Sensor	Capacity for long time submerged. Range of meter: -100 to 220 °C. Power supply: 3.3 - 5 $[V]$.

STM32F4110 microcontroller

Currently, the USV requires 4 communications ports (2 UART serial ports for LoRa and GPS modules and 2 I^2C ports for MPU and DST800). Most low-cost microcontrollers only have 1 UART serial port and 1 I^2C port. It is necessary to consider a microcontroller with multiple communication ports that meet the requirements for USV functionality (also, it is recommendable to consider a microcontroller with more communication channels for future work in case more sensors, devices, or instruments are required). This project proposes the microcontroller STM32F4110 as a good option that meets the requirements. Table 4.2 presents the main features of this microcontroller.

Table 4.2: Main characteristics of STM32F4110 microcontroller.

Characteristic	Description
Clock	4-26$[MHz]$ internal crystal oscillator. Up to 100$[MHz]$ with PPL.
Inputs/Outputs	Up to 81 I/O ports (78 fast I/O up to 100$[MHz]$)
A/D converter	One 12-bit ADC with up to 16 channels.
Communication interfaces	Up to 3 I^2C, 3 USART, 5 SPI/I2S, 1 SDIO, and 1 USB 2.0 full-speed

Also, other materials were used, like cables, connectors, terminals, materials for welding, and general electronic materials like resistors and capacitors.

The two DC motors consider reusing two Flytec 2011-5 Fishing RC Boat Motors designed for underwater operation. Figure 4.6 presents these motors.

Figure 4.6: Flytec 2011-5 Fishing RC Boat Motors.

In the case of the CU, it requires:

- Raspberry Pi.
- Display screen.
- LoRa transceiver module E220-900T22D.

The transceiver is the same for both, CU and USV.

Also, elaborating the prototype structure requires other materials. These consider:

- Container for electronic and circuits.
- Screws and nuts.
- Support structure to hold container and join both buoyancy elements.
- 2x buoyancy elements.

The buoyancy elements and the support structure must consider inert material.

The next step considers implementing the algorithms related to the functionality of advance. The following section introduces the proposed algorithms.

4.2 Algorithms proposed

In order for proving the hypothesis, two algorithms are required. The first algorithm is the point-to-point monitoring. Figure 4.7 introduces the proposed process for this monitoring process.

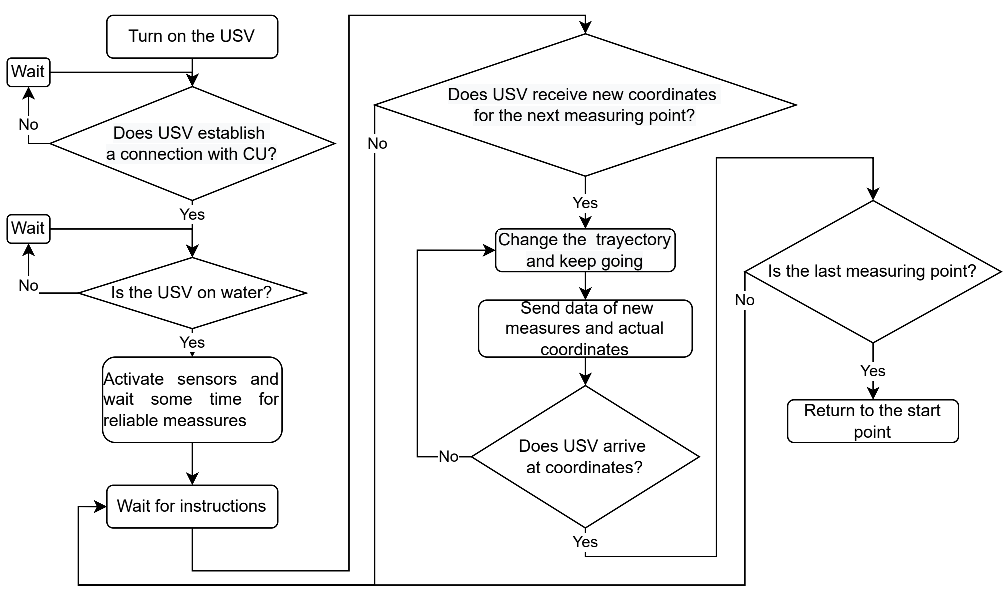

Figure 4.7: Proposed process for point-to-point monitoring.

In the case of the second algorithm, Figure 4.8 introduces the proposed process for continuous monitoring.

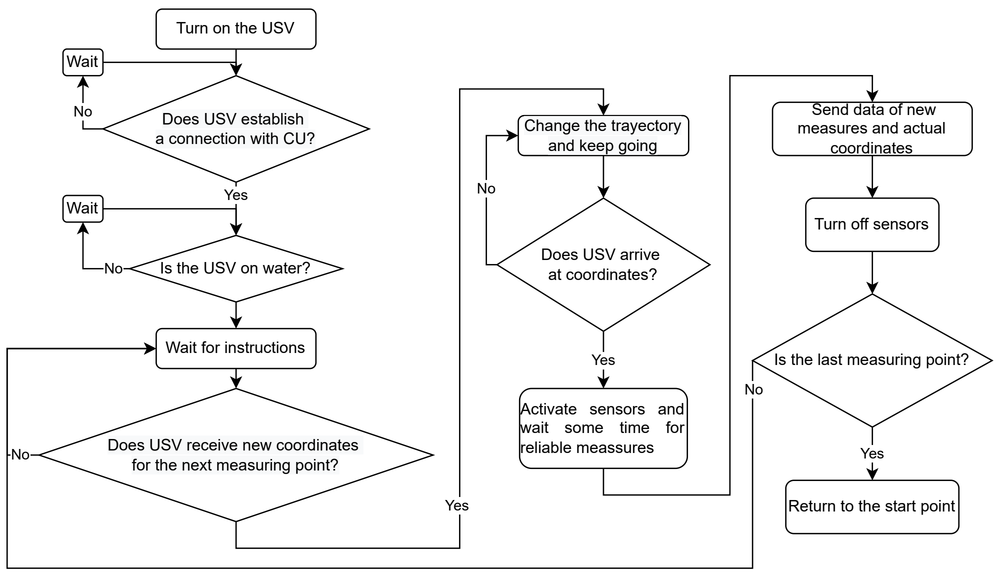

Figure 4.8: Proposed process for continuous monitoring.

To understand how each algorithm affects the monitoring process, Figure 4.9 presents both cases with the same route.

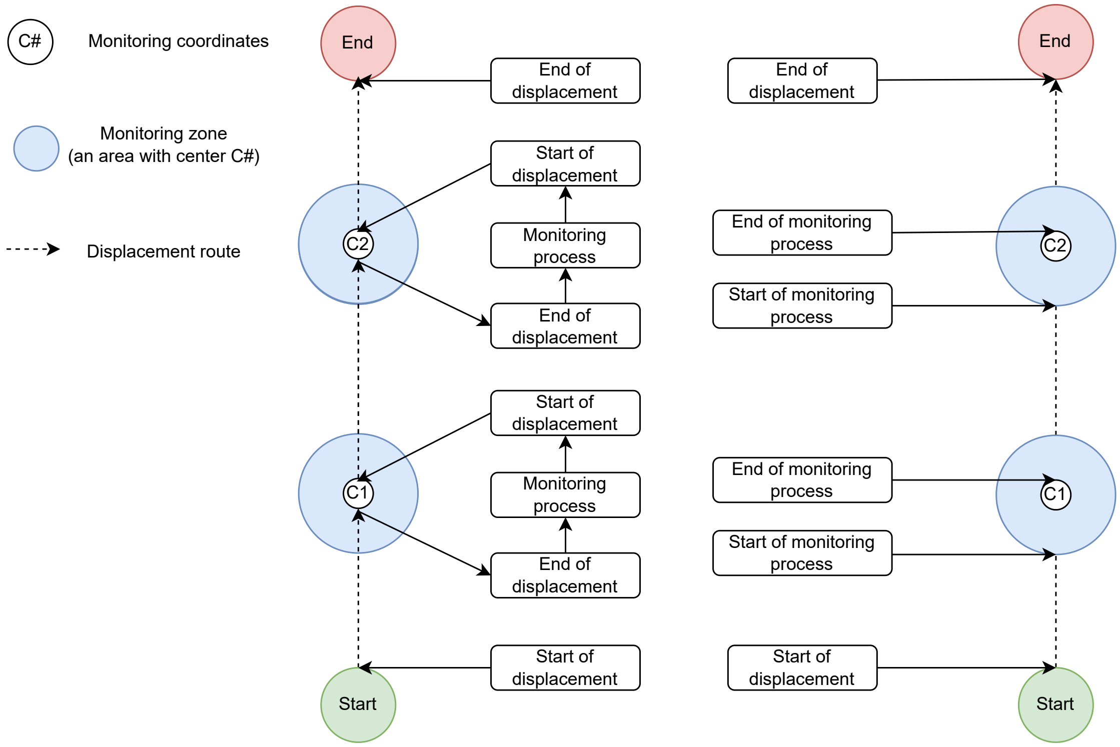

Figure 4.9: Example of behavior of USV with each algorithm.

In Figure 4.9, blue circles represent an area. These are considered zones where the monitoring process can be achieved (only inside the blue area). Figure 4.10 details the monitoring area.

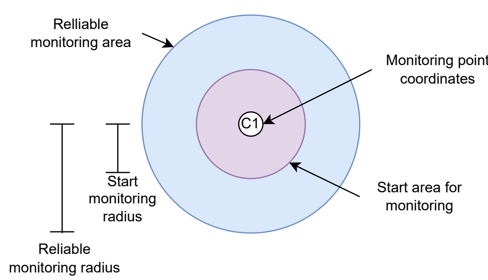

Figure 4.10: Details of monitoring area.

The number of monitoring points can vary according to the necessities of the experimentation stage; Figure 4.11 introduces an example of the same route with different numbers of monitoring spots.

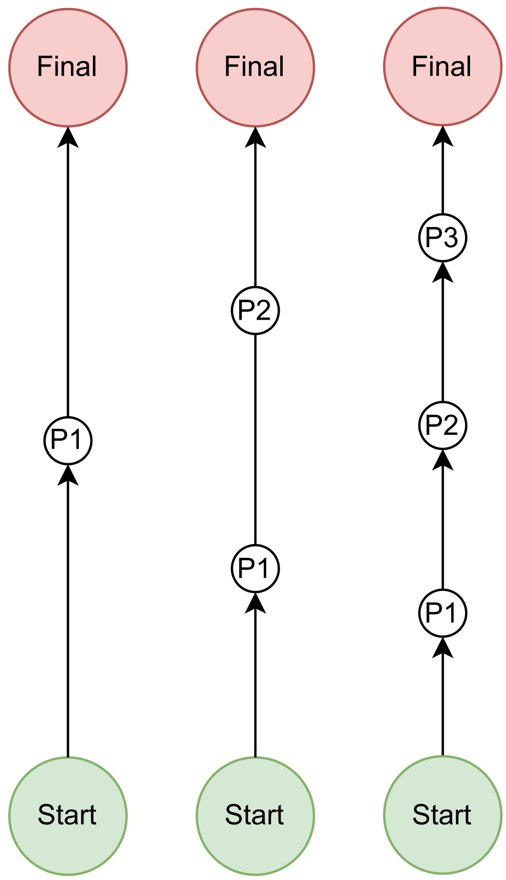

Figure 4.11: Example of different number of monitoring points.

Figure 4.12 describes how the monitoring types must be implemented to obtain reliable data for comparing results.

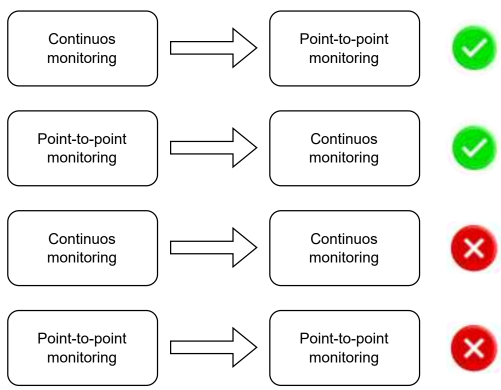

Figure 4.12: Order recommended for testing monitoring algorithms.

4.3 Experimentation

Before each experimentation process, it was necessary to verify the following points:

- USV hulls have no water leaks,
- battery is full-charged,
- USV communicates with the CU, which receives data in real time,
- All sensors and devices work without problems, and the data transmitted is reliable.

In case some problems were found, it was necessary to implement corrections and avoid starting any experimentation stage. Once all is fixed, proceed to implement the next steps for the experimentation stage:

1. Program the microcontroller with the first algorithm (point-to-point monitoring) and verify its correct functionality. See Figure 4.7 for reference.
2. Implement in a controlled environment (like a pool or similar) the USV and start a monitoring process.
3. Once the monitoring process is completed, apply data cleaning methods with the CU to delete and replace data out of range and missing data.
4. Analyze the data obtained with the CU for the quality of measurements and the energy consumption of the USV.
5. After completing the monitoring process with the first algorithm, immediately program the microcontroller with the second algorithm (continuous monitoring); see Figure 4.8 for reference.
6. Implement the USV in the same controlled environment and start a monitoring process.
7. Repeat steps 3 and 4 for data cleaning and analysis.
8. Perform steps 1 to 7 several times, alternating the order in which both algorithms are implemented in the USV to obtain enough data.
9. Analyze all the data, compare both algorithms and conclude.

CHAPTER 5

Results

In section 5, the prototype developed and the results obtained are introduced. The results are also analyzed.

5.1 Prototype development

As a result of 3D printing, a post-process, and instrumenting the USV, Figure 5.1 presents the prototype developed:

Figure 5.1: Isometric view of the prototype.

This version of the prototype contains:

- 2100 $[mAh]$ LiPo battery with a $5[V]$ module for energization of the main circuit and sensors, and 2300 $[mAh]$ LiPo battery for energization of the DC motors and L298N modules.
- Water quality sensors for pH, DO, and temperature parameters, with their respective modules.
- An INA219 electrical voltage/current/power sensors.

- A 5[km] LoRa communication module.
- 1 GPS module GT-U7.
- 2 modules L298N and 6 4N25 optocouplers.
- 2 Flytec 2011-5 DC motor.
- 1 STM32F411 microcontroller.

Figures 5.1, 5.2, 5.3, 5.4, 5.5, 5.6, 5.7, and 5.8 present different views of the prototype and its components.

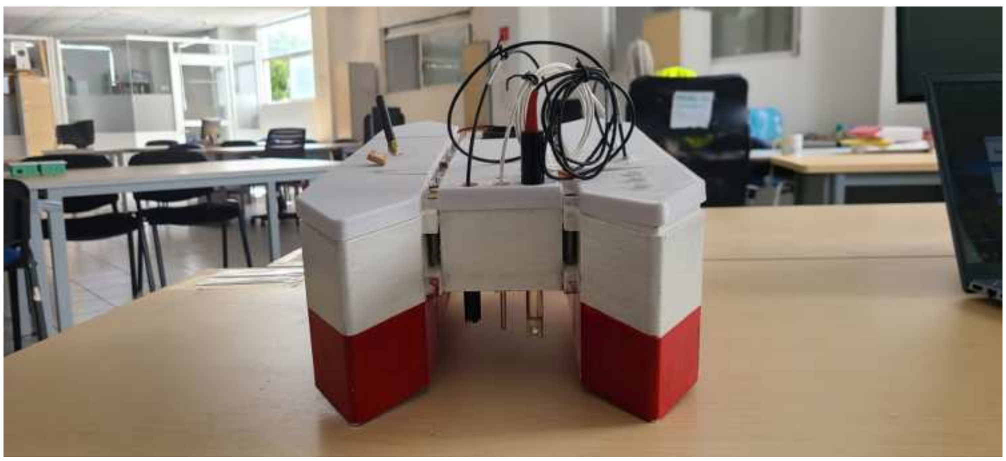

Figure 5.2: View of the sensors installed inside USV.

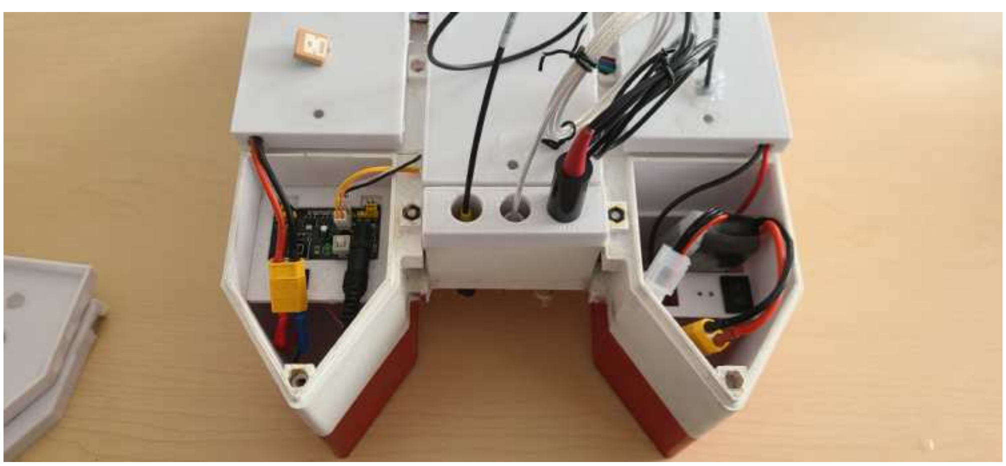

Figure 5.3: View of the batteries for USV energizing.

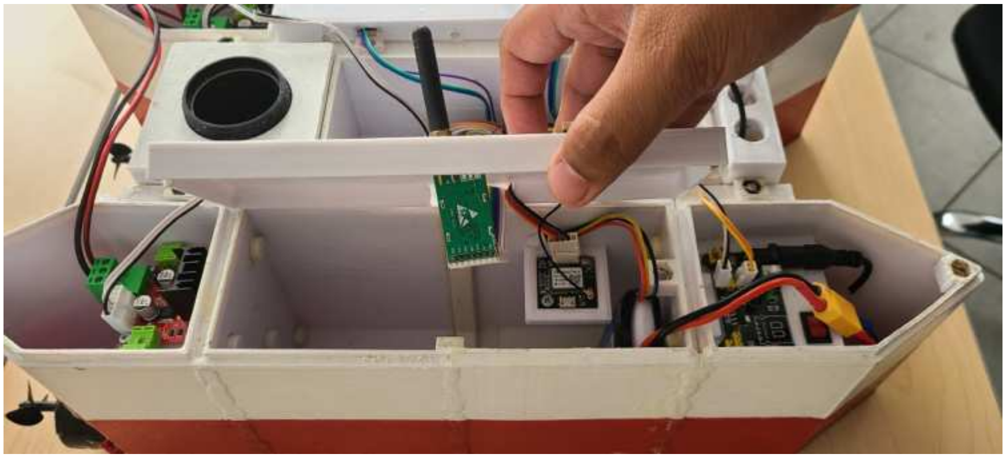

Figure 5.4: View of the right hull.

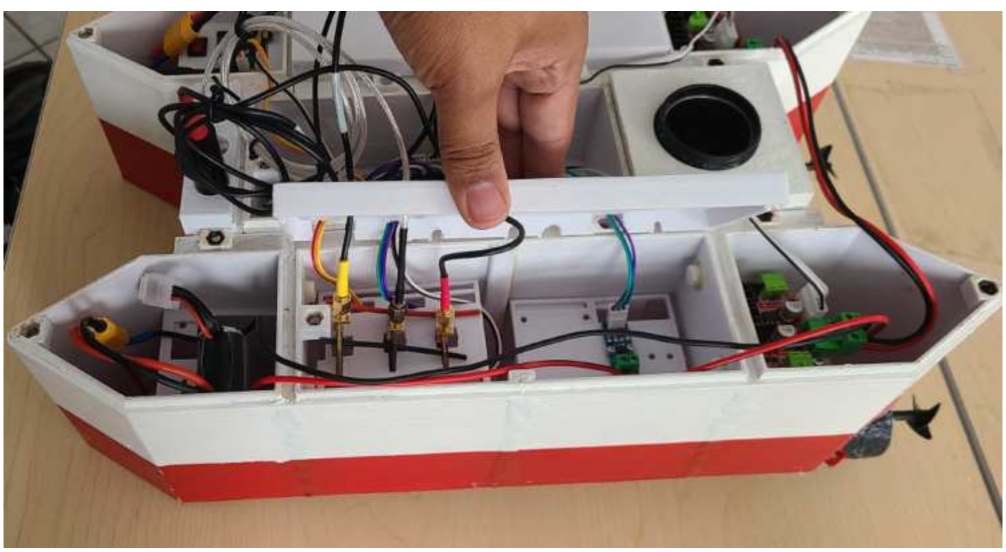

Figure 5.5: View of the left hull.

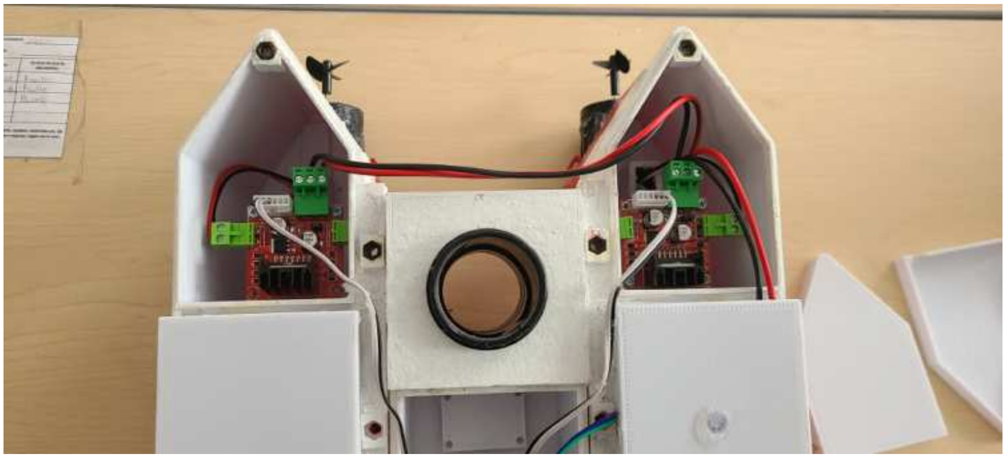

Figure 5.6: Superior view of the L298N and the Flytec DC motors.

Figure 5.7: Back view of the Flytec DC motors.

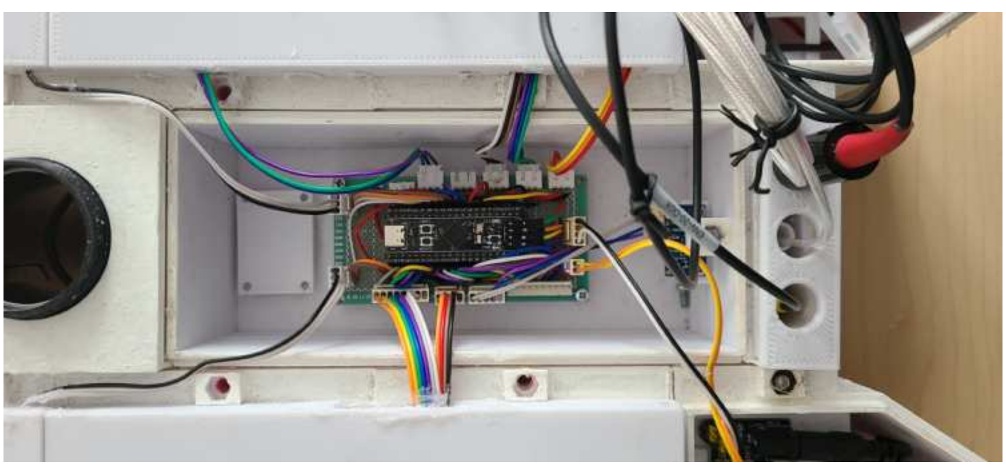

Figure 5.8: Superior view of the main circuit hull.

Some modules and sensors were not used in the final version of the prototype. These are:

- DST810 depth transducer and CAN-SPI module MCP2515: the principal reason is that microcontroller STM42F411 does not have CAN protocol communication. Because of this, MCP2515 was proposed to communicate via SPI with the transducer. Despite having this solution, no combination of the configuration registers provides the $235[kHz]$ communication frequency for the transducer.
- The 9-degree IMU 9250 is implemented but not used because both DC motors do not work equally. It affects the move forwards of the USV, causing a not desired turn-right or turn-left effect.

The final characteristics of the USV prototype are:

- Dimensions: $45[cm]$ length, $32[cm]$ width, and $13[cm]$ height (without motors).
- Weight: $4.87[kg]$.
- Capacity: $9.5[kg]$ before sink.

Figures 5.9, 5.10, 5.11, and 5.12 show the USV from different views when it is floating inside a water pool.

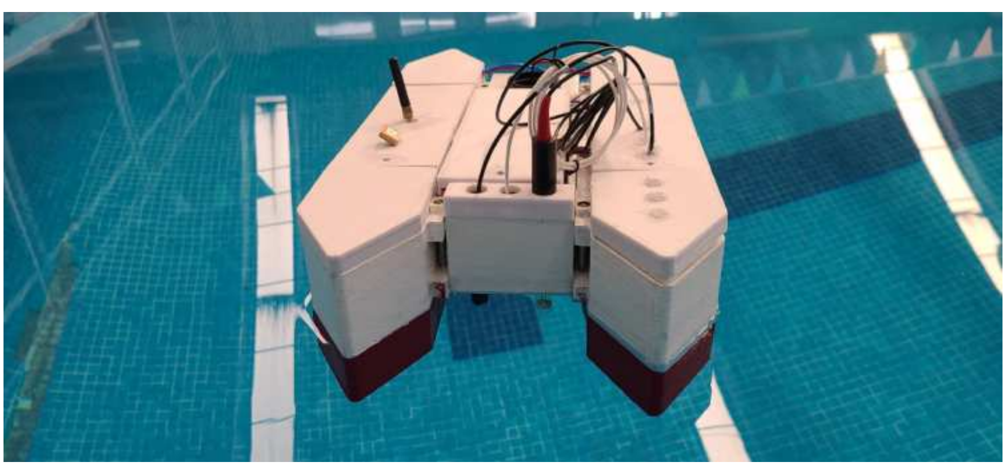

Figure 5.9: Frontal view of the USV inside the pool.

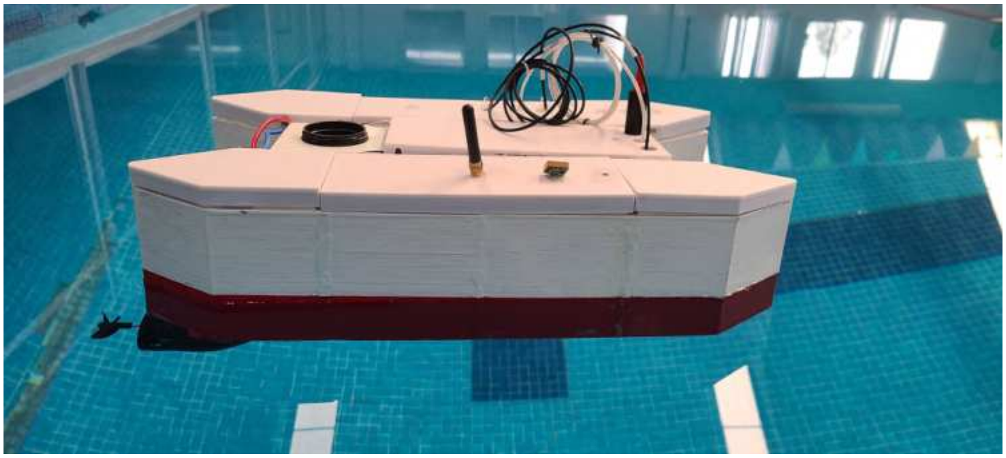

Figure 5.10: Right view of the USV inside the pool.

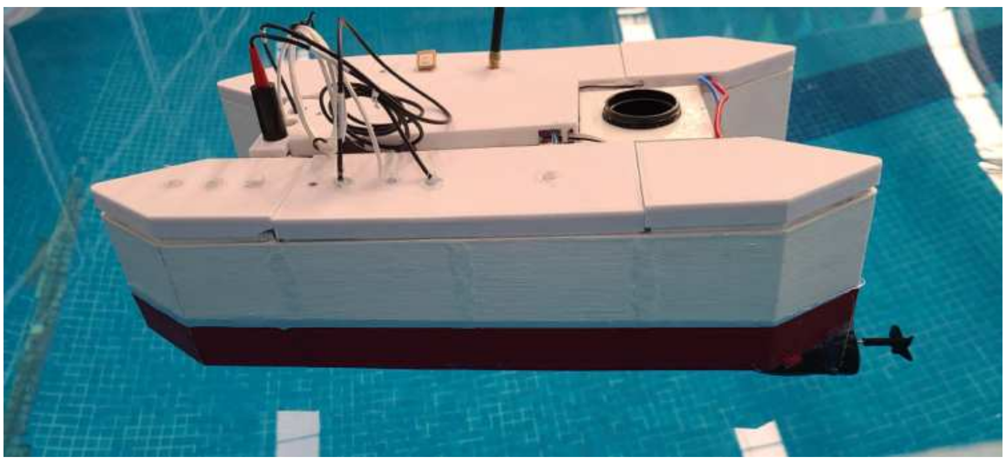

Figure 5.11: Left view of the USV inside the pool.

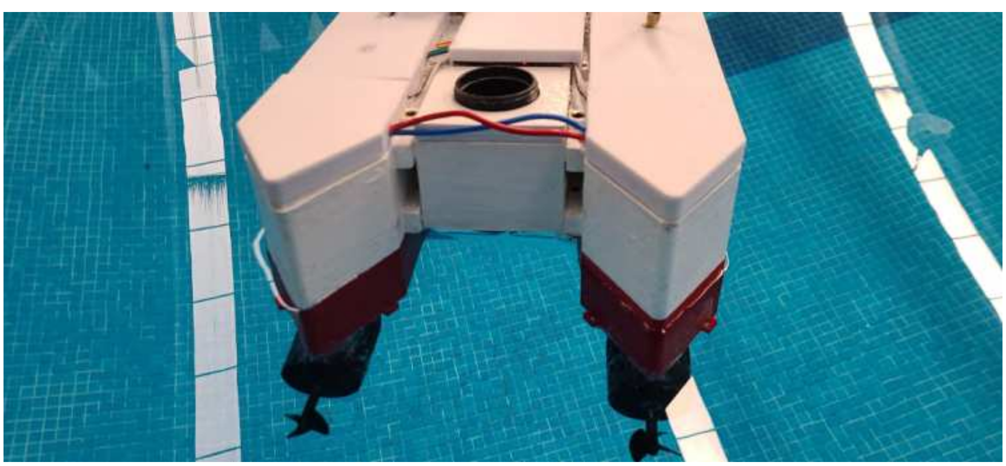

Figure 5.12: Back view of the USV inside the pool.

5.1.1 Graphical user interface

A graphic user interface (GUI) was developed to control the USV and receive data from the sensors. Figure 5.13 shows the GUI.

Figure 5.13: Graphical user interface for USV controlling.

The GUI in Figure 5.13 was developed in Python 3 with the *Tkinter* and *Tkintermapview* libraries and allowed to perform the following functions:

- Establish communication with the USV.
- Manage databases for storing the received data and exporting it to *Excel* tables.
- Sending the points of interest for the monitoring route.
- History of messages received and commands sent.
- Activation and management of sensors.
- Control over the direction of the USV and speed of motors.
- Display of the data received by the sensors.

5.1.2 Results obtained

Due to the bad quality of DC Motors, many problems were found. The energization of the propel-axes affected the measurements from sensors. In total, 6 DC motors were acquired, and 4 have this problem. The last two functional motors were acquired after the four motors with the problem. However, all three left-motors do not work as right-motors, which causes an inadequate control of the USV when trying to follow a straight line. To acquire good measurements, the USV followed a circular path when it was moving (to obtain measurements similar to those expected in continuous monitoring). Also, some measurements were acquired when the USV was not moving (to obtain measurements identical to those expected in point-to-point monitoring).

Measurements while USV is not moving

During the test, with no movement, the motors were activated at different periods of time in order to observe if these introduced noise to the measurements. Figure 5.14 introduces the voltage and current levels of the USV during this test.

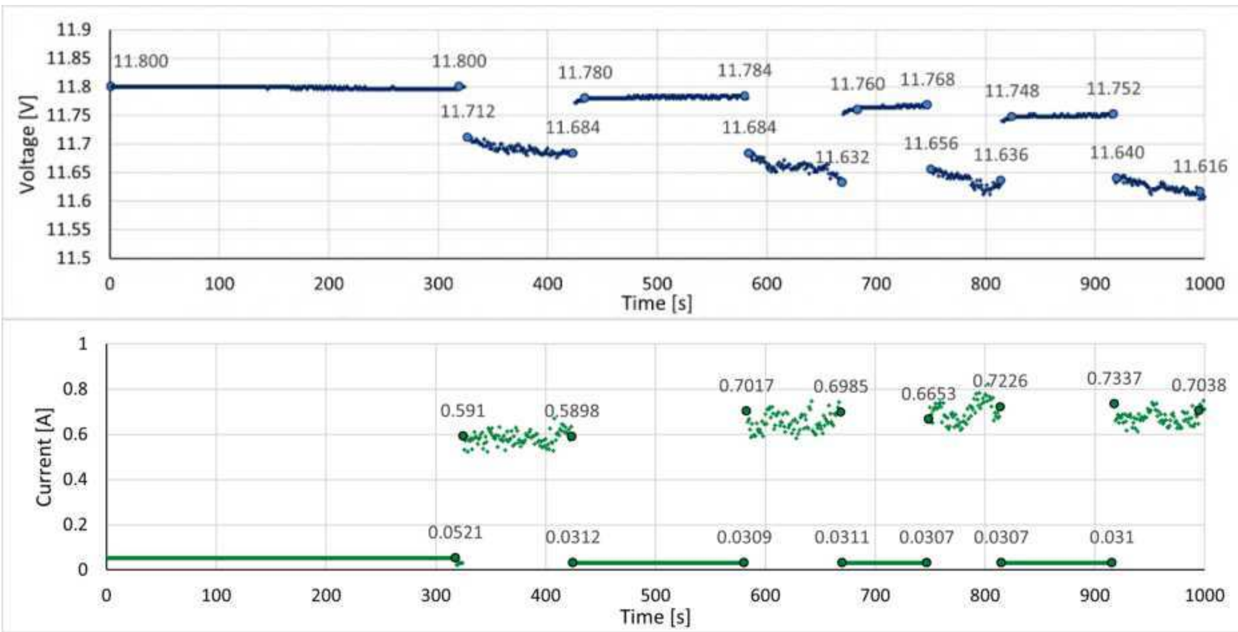

Figure 5.14: Graph of the voltage levels and the current consumed for the case with no movement.

Also, Figure 5.15 allows observing the electrical power consumed by the motors during the test at rest.

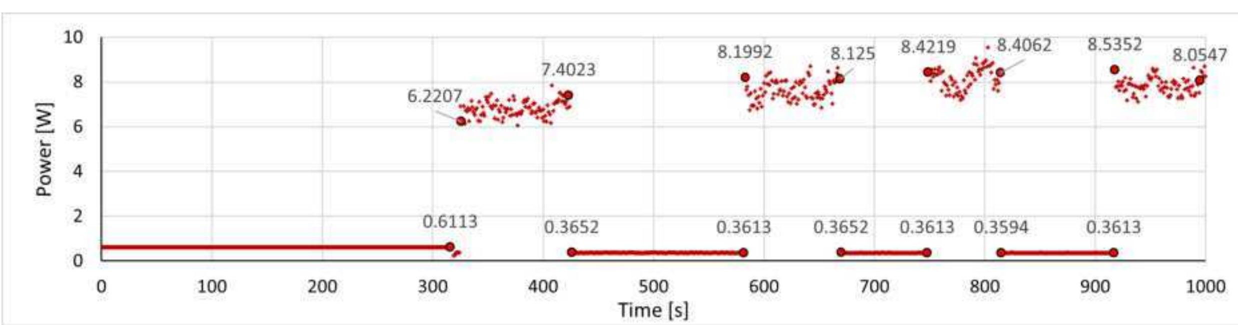

Figure 5.15: Graph of the electrical power consumption for the case with no movement.

When the DC motors are turned on, a drop occurs in voltage levels. After some time, the battery voltage level decreased due to the consumption of power. The behavior of the DO and pH sensors is presented in Figure 5.16:

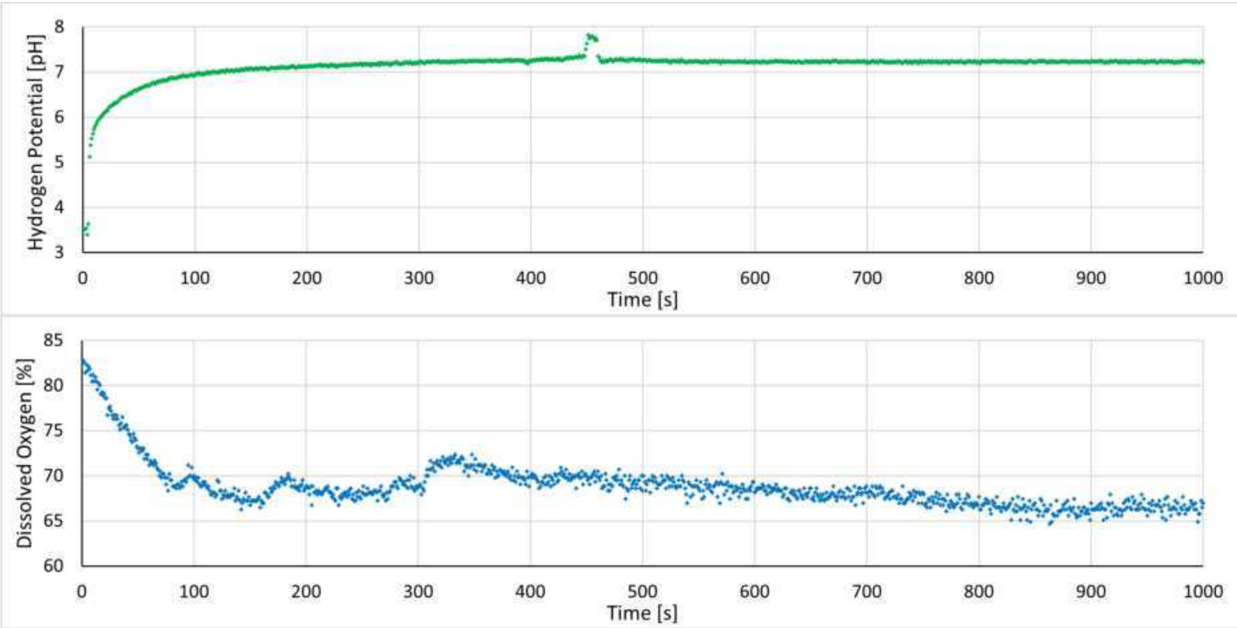

Figure 5.16: Behavior graph of the pH and DO sensors in the case with no movement.

The pH value changed by nearly 460[s] caused by the mixture of different water. Also, the temperature presented a change of value at the same time. Figure 5.17 presents the graph of the behavior of the temperature sensor:

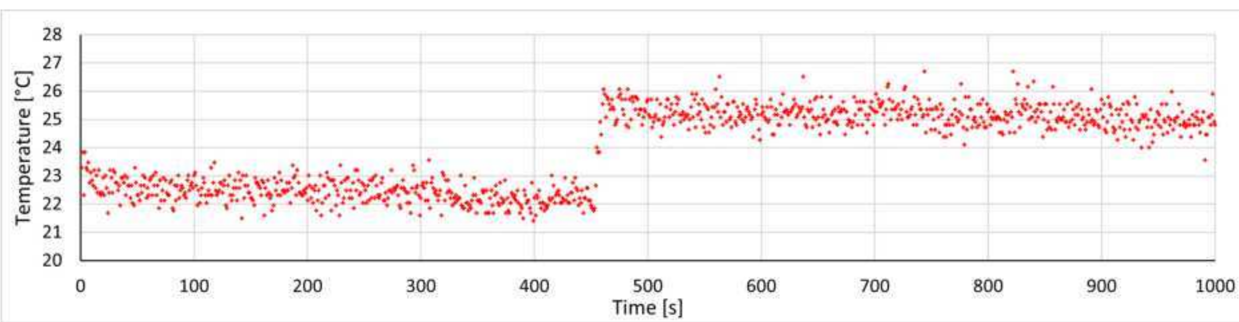

Figure 5.17: Behavior graph of the temperature sensor in the case with no movement.

When analyzing all previous graphs, it is possible to see that:

- There is no introduction of noise to the measurements due to the power stage of the motors.
- The temperature sensor and the DO sensor have variability in their measurements. It is most probably to be caused due to the resolution of the ADC, which is 12-bit.

Practical test without the pH sensor

The next figures introduce the behavior of all sensors and electrical consumption when the pH sensor is not submerged. Figure 5.18 introduces the voltage and current levels of the USV when stopped or moving:

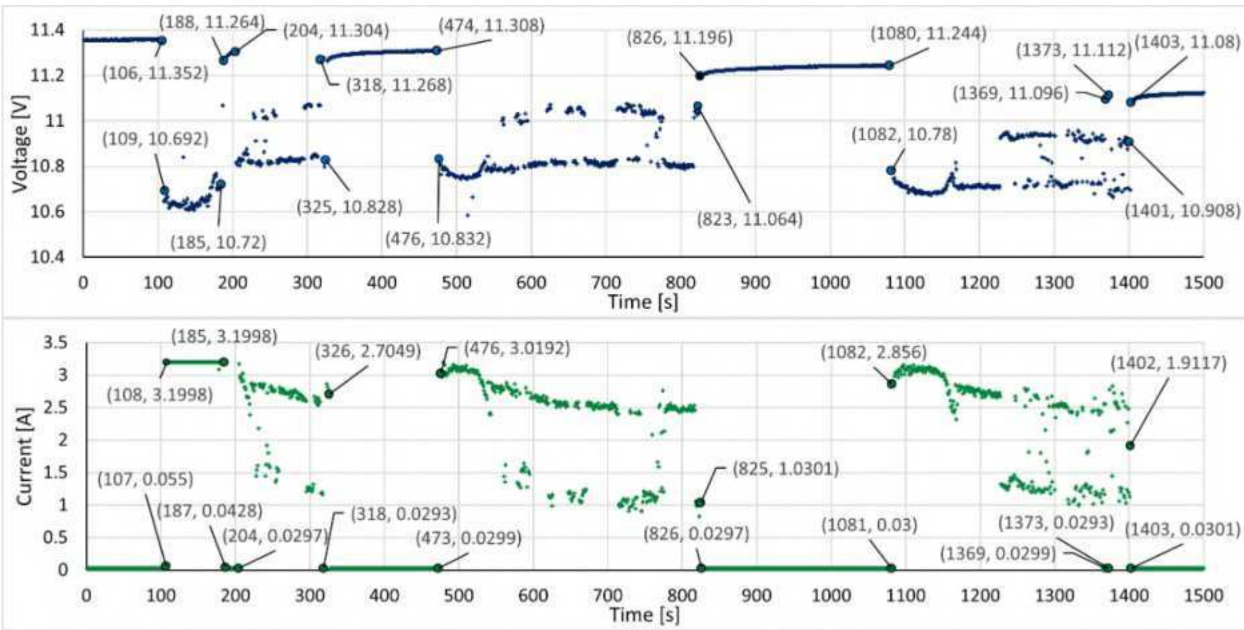

Figure 5.18: Graph of the voltage levels and current consumed for the case of the submerged DO sensor.

The behavior of current measures between 108[s] and 185[s] is because these values exceed the current limit of the INA219, which is 3.2[A]. It was caused because PWM was working at 50%. To avoid these, the PWM was used at 40%. All practical tests were obtained in a pool, and most of the measures were obtained while the USV was moving in circles, but sometimes, it was necessary to turn to the right or even stop to avoid collisions. Due to the malfunction of the left motor, when turning right, the electrical consumption was lower than when both motors were working to move straight or turn left. All values at the level of 11[V] are caused when USV was turning right, and all values at 10.8[V] are caused when USV was turning left or moving straight. In the case of Figure 5.19, it allows observing the electrical power consumed by the motors:

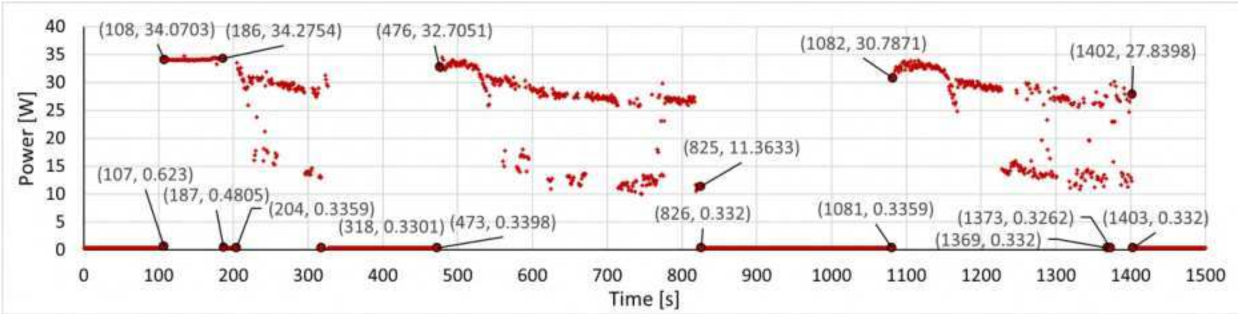

Figure 5.19: Graph of electrical power consumption for the case of the submerged DO sensor.

The behavior for sensors of DO and temperature are introduced in Figure 5.20:

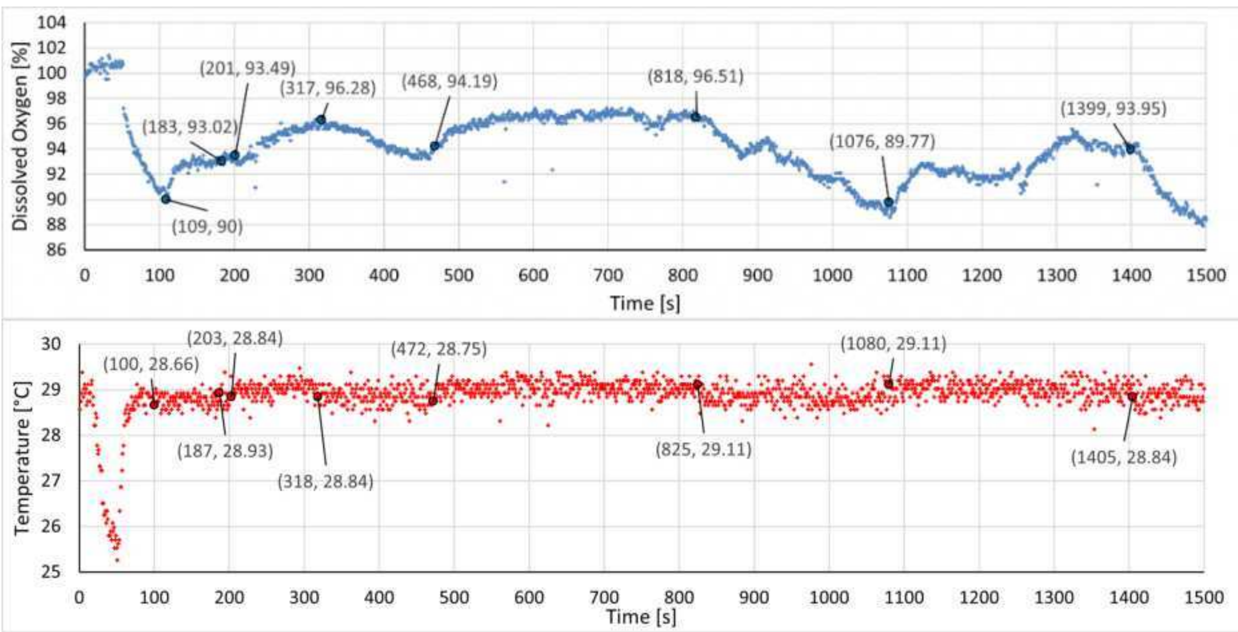

Figure 5.20: Behavior graph of the temperature and dissolved oxygen sensor in the case of the submerged DO sensor.

The measurements before 50[s] are caused when USV was outside of water. When USV was introduced in water, temperature and DO values change. At 109[s], the USV test started. When comparing the graphs of the sensor measurements with those of electrical consumption, it can be noticed that:

- At times when the USV is moving, it is observed that the OD value increases.
- When the USV is not moving, the OD value decreases.
- Sometime after 468[s], when the USV is moving, the OD values were stabilized and did not continue to grow.

- In the case of the temperature sensor, when the USV is moving, its measurements are also affected, but very slightly.

Practical test without the DO sensor

The next figures introduce the behavior of all sensors and electrical consumption when the DO sensor is not submerged. Figure 5.21 introduces the voltage and current levels of the USV when stopped or moving.

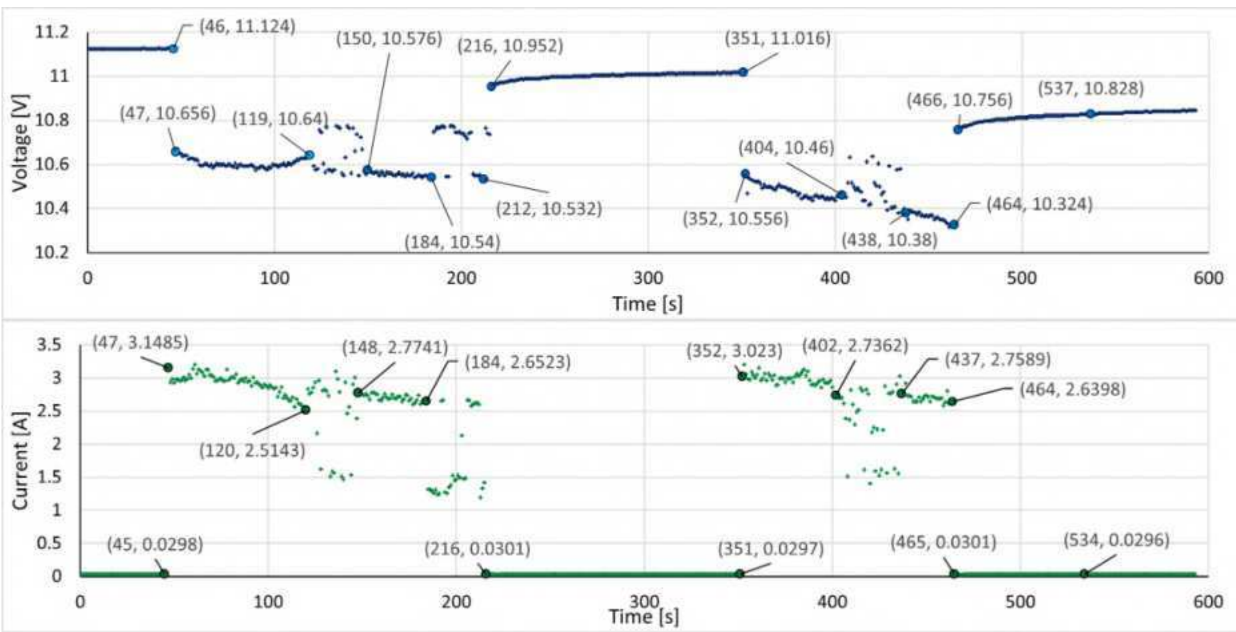

Figure 5.21: Graph of the voltage levels and current consumed in the case of the submerged pH sensor.

In this test, sometimes, it was required to turn right; all voltage values around $10.8[V]$ before time $216[s]$ represent these moments, while values below $10.656[V]$ represent moments when USV was turning in circles to the left. The same behavior is observed after time $352[s]$. In the case of Figure 5.22, it allows observing the electrical power consumed by the motors.

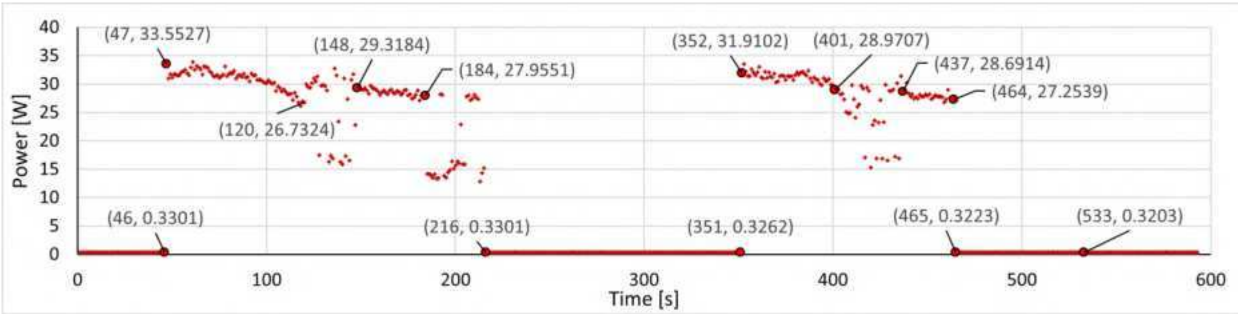

Figure 5.22: Graph of the electrical power consumption in the case of the submerged pH sensor.

The response of the pH and temperature sensors are introduced in Figure 5.23:

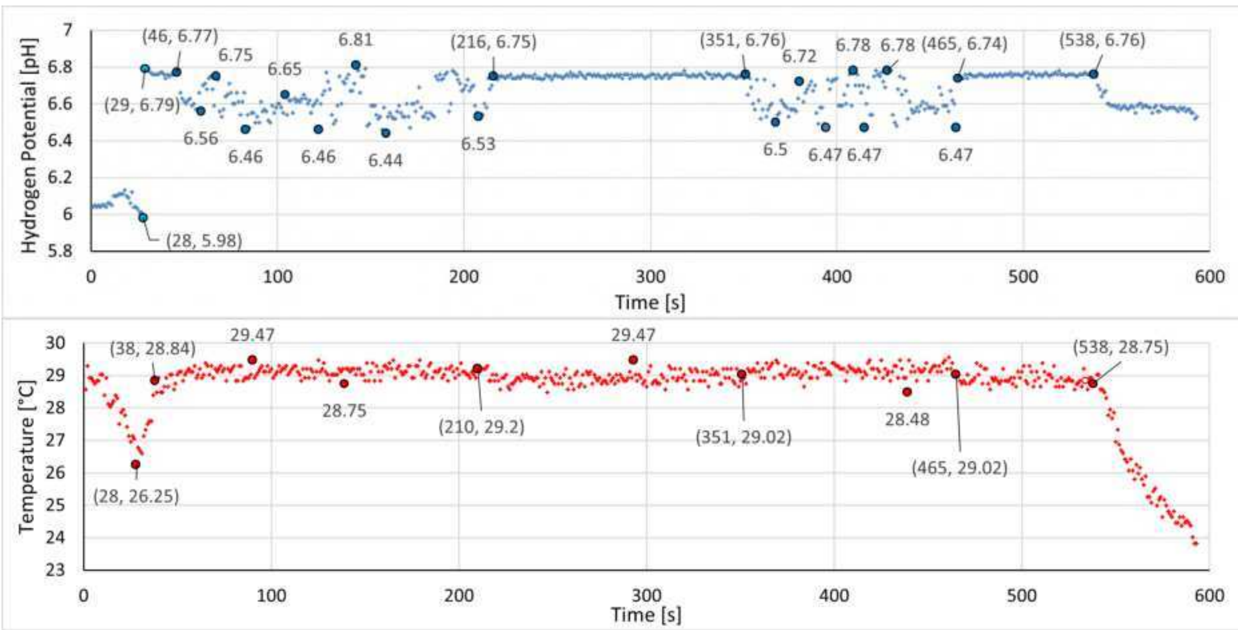

Figure 5.23: Behavior graph of the temperature and pH sensor in the case of the submerged pH sensor.

The next points describe some behaviors found when comparing the graphs of the sensor measurements with that of electrical consumption:

- At times when the USV is in motion, it is observed that the pH value varies.
- When the USV is not moving, the pH value remains constant.
- pH values usually vary, but apparently they have a range of variation; in this case, the measurements did not decrease below $6.46[pH]$, between $46[s]$ and $216[s]$, or $6.47[pH]$, between $351[s]$ and $465[s]$.
- In the case of the temperature sensor, when the USV is moving, its measurements are also affected, but very slightly.

Ideal case for monitoring types

In order to have a better comparison between continuous monitoring and point-to-point monitoring, an ideal case is presented considering that:

- The USV presents a constant advance, so the time it takes to travel from one monitoring point to another will be the same, which is $100[s]$.
- In the case of the point-to-point monitoring, a time of $120[s]$ is considered to obtain the data from the sensors.
- The data used corresponds to the measurements and behaviors observed previously, where they are divided into data affected and not affected by the movement.

Figure 5.24 presents the comparison of the types of monitoring using an ideal case.

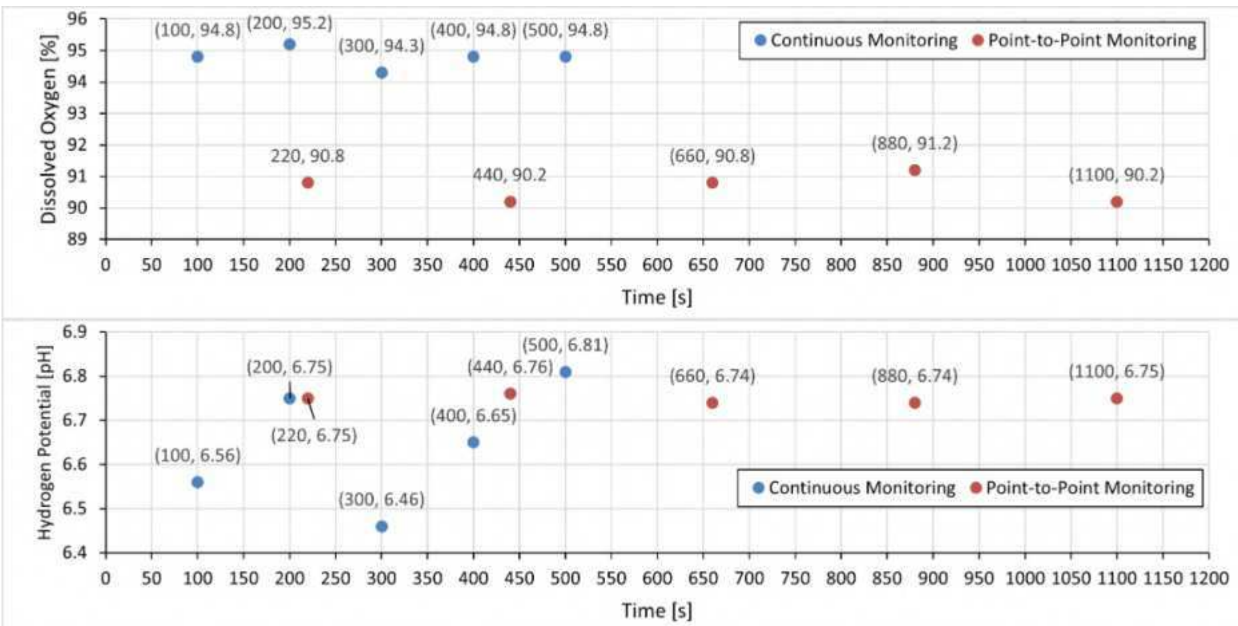

Figure 5.24: Comparison of monitoring types in pH and DO sensor measurements.

Considering Figure 5.24, next points introduced some statements:

- The type of monitoring that has the shortest monitoring time is continuous monitoring.
- Sensors are affected by movement, some more than others; in the case of the pH sensor, it is the one that is affected the most. However, it seems that their variations are within the same range. The recommendation in this case is considering that the pH value has an error of $+0.2[pH]$ (according to the observed in Figure 5.23). The sensor that is least affected by movement is the temperature sensor.
- In the case of the OD sensor, the value is affected such that it increases; however, after a while, the value stabilizes. The difference between both stabilized values is approximately of

8[%].

Engine consumption analysis

To better understand energy consumption, Figure 5.25 presents the voltage and current consumption of the motors during startup:

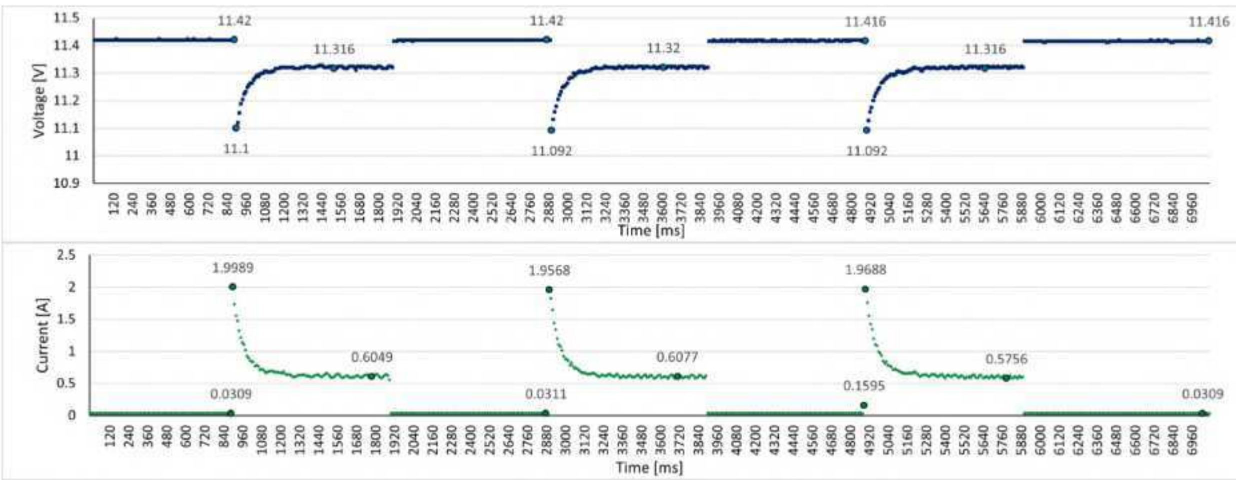

Figure 5.25: Graph of voltage and current levels during motor starting.

While Figure 5.26 presents the power consumption of the motors during startup:

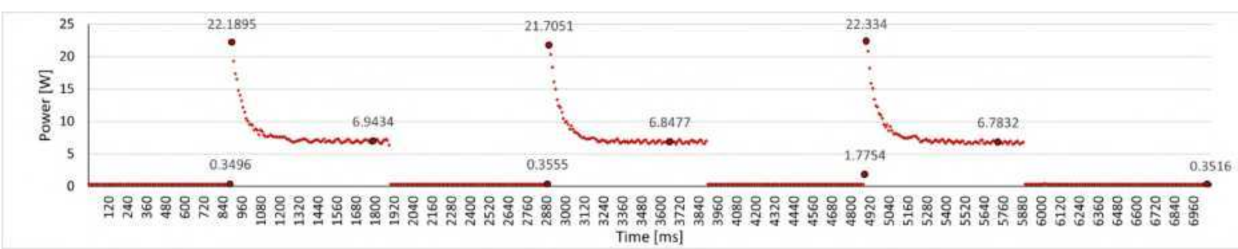

Figure 5.26: Graph of the power consumed during engine startup.

The peak power consumption is made in 200$[ms]$ with an average of 12.065$[W]$, while the subsequent consumption presents an average of 7.108$[W]$. However, despite the difference between the two, in a practical test, the peak power consumption should not be affected so much because, in continuous monitoring, it would only occur once; this is not the case with point-to-point monitoring where it occurs in the same number of times as there are points to monitor.

The comparison of this can be seen in Figure 5.27:

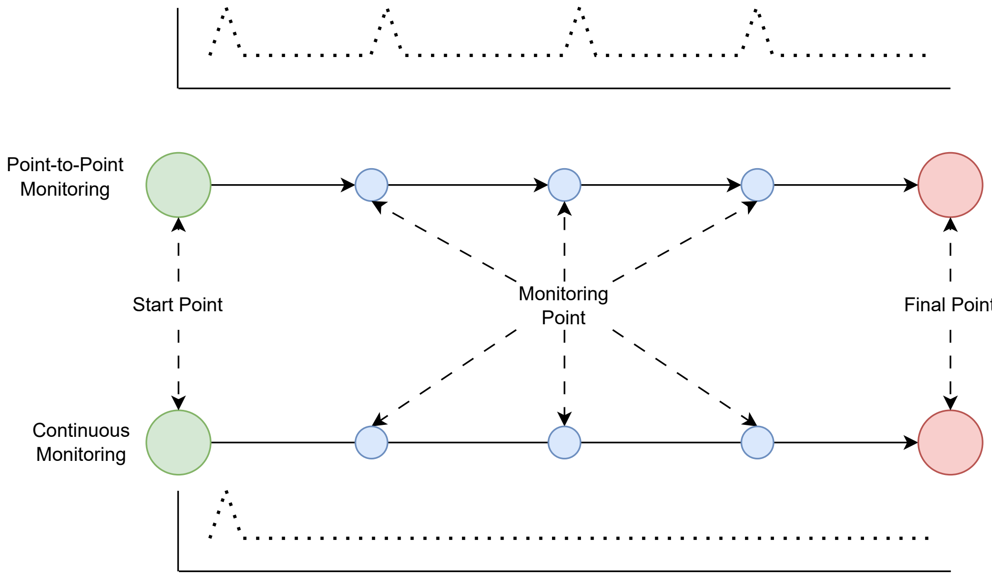

Figure 5.27: Comparison of current consumption for point-to-point monitoring and continuous monitoring.

Even if the current consumption from the microcontroller is $0.11[A]$ and from sensors (pH, temperature, and dissolved oxygen) is $3.5[mA]$ ($3[mA]$, $0.2[mA]$ and $0.3[mA]$ respectively), at a constant voltage level of $4.95[V]$, the electrical consumption is still greater in point-to-point monitoring. The main cause is due to the total time in which the USV is active, compared to continuous monitoring.

CHAPTER 6

Conclusions

From the analysis of the results in the different cases presented, it is observed that the sensor measurements are affected by the displacement of the USV, some more than others. However, these alterations seem to be within a range. Despite these being altered values, the real value could be predicted. Thus, it can be considered that:

- Point-to-point monitoring offers the advantage of having reliable measurements. However, it offers the disadvantage of greater energy consumption and monitoring time.
- Continuous monitoring offers the advantage of having lower energy consumption and monitoring time. However, the measurements are altered by movement, although according to what has been observed, the pH values are seen within a slightly smaller range than expected and those of OD slightly higher.

Considering the case presented in Figure 5.27 and the analysis carried out, it is observed that the type of continuous monitoring has low consumption monitoring compared to point-to-point monitoring. In this way, the hypothesis is accepted.

The main contribution of the project is technological, since from the investigation of the state of the art it was observed that until that moment a similar project did not exist in the country. In addition, it offers a new tool for monitoring and protecting freshwater bodies in the country. Regarding the contribution to the existing literature, the advantages/disadvantages of choosing any of the two types of monitoring presented can be highlighted.

However, it is recommended to continue investigating how exactly the USV displacement affects the sensors, and mainly how the variation in the displacement speed affects the variations in the measurements. In addition, due to the various problems that were presented and the various areas of improvement, it is proposed to make the following proposals in the future:

1. Develop an own-design displacement system to avoid the need to import submersible motors from China and avoid the problems presented during the tests.

2. Improve the insulation of the USV against humidity to protect the interior of the USV, which can cause different problems in the circuits.

3. Migrate the code to an STM Nucleo development board, which allows the DST810 transducer to be implemented.

4. Modify the resistance of the INA219 current sensor to detect currents greater than $3.2[A]$.

5. Determine how the speed of the USV affects the sensor measurements.

6. Implement automatic control of the USV and algorithms for automatic monitoring.

Bibliography

[1] P. A. Krenkel and V. Novotny, "Water quality management," 1980.

[2] World Health Organization, "Volume 1 coastal and fresh waters," in *GUIDELINES ON RECREATIONAL WATER QUALITY*, p. 164, Amsterdam: Elsevier, 2021.

[3] A. H. Kelechi, M. H. Alsharif, A. C. Anya, M. U. Bonet, S. A. Uyi, P. Uthansakul, J. Nebhen, and A. A. Aly, "Design and implementation of a low-cost portable water quality monitoring system," *Computers, Materials and Continua*, vol. 69, no. 2, p. 2405 – 2424, 2021.

[4] D. and M. Pérez, A. Farfan, and E. Gerlein, "Idc sensor for low-cost water quality monitoring applications," *Computers, Materials & Continua*, vol. 26, 2022.

[5] M. R. D. Molato, "Aquastat: An arduino-based water quality monitoring device for fish kill prevention in tilapia aquaculture using fuzzy logic," *International Journal of Advanced Computer Science and Applications*, vol. 13, 2022.

[6] L. Parra, G. Lloret, J. Lloret, and M. Rodilla, "Physical sensors for precision aquaculture: A review," *IEEE Sens*, vol. 18, 2018.

[7] F. A. Saparudin, T. C. Chee, A. S. Ab Ghafar, H. A. Majid, and N. Katiran, "Wireless water quality monitoring system for high density aquaculture application," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 13, p. 507 – 513, 2019.

[8] K. S. Adu-Manu, F. A. Katsriku, J. D. Abdulai, and F. Engmann, "Smart river monitoring using wireless sensor networks," *Wireless Communications and Mobile Computing*, vol. 2020, 2020.

[9] H. C. Yu, M. Y. Tsai, Y. C. Tsai, J. J. You, C. L. Cheng, J. H. Wang, and S. J. Li, "Development of miniaturized water quality monitoring system using wireless communication," *Sensors (Switzerland)*, vol. 19, 2019.

[10] F. Lezzar, D. Benmerzoug, and I. Kitouni, "Iot for monitoring and control of water quality parameters," *International Journal of Interactive Mobile Technologies*, vol. 14, p. 4 – 19, 2020.

[11] A. C. Da Silva Junior, R. M. M. De Los Angeles Quezada, A. V. Lira Neto, M. M. Hassan, and V. H. C. De Albuquerque, "Internet of water things: A remote raw water monitoring and control system," *IEEE Access*, vol. 9, p. 35790 – 35800, 2021.

[12] L. V. Quoc Danh, D. V. Minh Dung, T. H. Danh, and N. C. Ngon, "Design and deployment of an iot-based water quality monitoring system for aquaculture in mekong delta," *International Journal of Mechanical Engineering and Robotics Research*, vol. 9, pp. 1170–1175, 2020.

[13] J. Zhang et al., "Design and analysis of a water quality monitoring data service platform," *Computers, Materials & Continua*, vol. 66, 2020.

[14] N. Thai-Nghe, N. Thanh-Hai, and N. C. Ngon, "Deep learning approach for forecasting water quality in iot systems," *International Journal of Advanced Computer Science and Applications*, vol. 11, 2020.

[15] H. C. Chang, Y. L. Hsu, S. S. Hung, G. R. Ou, J. R. Wu, and C. Hsu, "Autonomous water quality monitoring and water surface cleaning for unmanned surface vehicle," *Sensors (Switzerland)*, vol. 21, p. 1 – 21, 2021.

[16] E. Kim, N. Sook-Hyun, C. H. Ahn, S. Lee, J. W. Koo, and T. M. Hwang, "Comparison of spatial interpolation methods for distribution map an unmanned surface vehicle data for chlorophyll-a monitoring in the stream," *Environmental Technology and Innovation*, vol. 28, 2022.

[17] A. Odetti, G. Bruzzone, M. Altosole, M. Viviani, and M. Caccia, "Swamp, an autonomous surface vehicle expressly designed for extremely shallow waters," *Ocean Engineering*, vol. 216, 2020.

[18] Comisión Nacional del Agua, "Calidad del agua superficial 2020," 2021. Data base on Excel file.

[19] Y. Li, L. Tian, W. Li, J. Li, A. Wei, S. Li, and R. Tong, "Design and experiments of a water color remote sensing-oriented unmanned surface vehicle," *Sensors (Switzerland)*, vol. 20, 2020.

[20] H. Cao, Z. Guo, S. Wang, H. Cheng, and C. Zhan, "Intelligentwide-area water quality monitoring and analysis system exploiting unmanned surface vehicles and ensemble learning," *Water (Switzerland)*, vol. 12, 2020.

[21] X. Zhu, K. Yan, S. Kong, and Y. Yue, "4g-based remote manual control for unmanned surface vehicles," *ACM International Conference Proceeding Series*, 2019.

[22] M. D. Asif Hasan, H. Chen, Y. Lin, and X. Liu, "Wipi: An extendable edge platform for building time-critical cyber-physical-human systems," *ACM International Conference Proceeding Series*, 2019.

[23] O. L. Osen, A. Havnegjerde, V. Kamsvag, S. Liavaag, and R. T. Bye, "A low cost usv for aqua farm inspection," *Techno-Ocean 2016: Return to the Oceans*, p. 291 – 298, 2016.

[24] M. Zhou and J. Shi, "The design and development of an affordable unmanned surface vehicle for estuary research and stem education," *2020 Global Oceans 2020: Singapore - U.S. Gulf Coast*, 2020.

[25] C. Degel, L. Peter, M. Schmieger, H. Hewener, W. Bost, M. Ehrhardt, and S. Tretbar, "Hydrocrawler - an innovative autonomous surface vehicle for high precision underwater measurements," *OCEANS 2019 - Marseille, OCEANS Marseille 2019*, vol. 2019-June, 2019.

[26] S. Garuglieri, D. Madeo, A. Pozzebon, R. Zingone, C. Mocenni, and D. Bertoni, "An integrated system for real-time water monitoring based on low cost unmanned surface vehicles," *SAS 2019 - 2019 IEEE Sensors Applications Symposium, Conference Proceedings*, 2019.

[27] N. Wu and M. Khan, "Lora-based internet-of-things: A water quality monitoring system," *Conference Proceedings - IEEE SOUTHEASTCON*, vol. 2019-April, 2019.

[28] J. Balbuena, D. Quiroz, R. Song, R. Bucknall, and F. Cuellar, "Design and implementation of unmanned surface vehicle for water quality monitoring," *OCEANS 2017 - Anchorage*, vol. 2017-January, p. 1 – 8, 2017.

[29] S. Siyang and T. Kerdcharoen, "Development of unmanned surface vehicle for smart water quality inspector," *2016 13th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology, ECTI-CON 2016*, 2016.

[30] J. Matos and O. Postolache, "Iot enabled aquatic drone for environmental monitoring," *Proceedings of the 2016 International Conference and Exposition on Electrical and Power Engineering, EPE 2016*, p. 598 – 603, 2016.

[31] M. Li, Y. He, Y. Ma, and J. Yao, "Design and implementation of a new jet-boat based unmanned surface vehicle," *IET Conference Publications*, vol. 2012, p. 768 – 771, 2012.

[32] Y. Wen-Rong, C. Cing-Ying, H. Chao-Min, T. Chiung-Jung, and Y. Wen-Chang, "Multifunctional inshore survey platform with unmanned surface vehicles," *International Journal of Automation and Smart Technology*, vol. 1, p. 19 – 25, 2011.

[33] J. Wang, W. Gu, J. Zhu, and J. Zhang, "An unmanned surface vehicle for multi-mission applications," *Proceedings - 2009 International Conference on Electronic Computer Technology, ICECT 2009*, p. 358 – 361, 2009.

[34] Z. Gao, "Research on information sensing and transmitting technology for island using 5g system," *IEEE 2nd International Conference on Electronic Technology, Communication and Information*, vol. ICETCI 2022, 2022.

[35] J. Balbuena et al., "Design and implementation of an usv for large bodies of fresh waters at the highlands of peru,," *in OCEANS 2017*, 2017.

[36] P. Dash et al, "Evaluation of water quality data collected using a novel autonomous surface vessel," *in Oceans Conference Record (IEEE)*, vol. 2021-September, 2021.

[37] D. Sousa, M. Luís, S. Sargento, and A. Pereira, "An aquatic mobile sensing usv swarm with a link quality-based delay tolerant network," *Sensors (Switzerland)*, vol. 18, 2018.

[38] W. Chen, X. Hao, K. Yan, J. Lu, J. Liu, C. He, F. Zhou, and X. Xu, "The mobile water quality monitoring system based on low-power wide area network and unmanned surface vehicle," *Wireless Communications and Mobile Computing*, vol. 2021, 2021.

[39] V. Nikishin, M. Durmanov, and I. Skorik, "Autonomous unmanned surface vehicle for water surface monitoring," *TransNav, the International Journal on Marine Navigation and Safety of Sea Transportation*, vol. 14, 2020.

[40] M. Elkolali et al, "A low-cost wave-solar powered unmanned surface vehicle," *Global Oceans 2020: Singapore – U.S. Gulf Coast*, vol. October 2021, 2022.

[41] E. Pairet et al, "Nukhada usv: a robot for autonomous surveying and support to underwater operations," *OCEANS 2022 - Chennai, 2022*, vol. October 2022, 2022.

[42] A. Totland and E. Johnsen, "Kayak drone – a silent acoustic unmanned surface vehicle for marine research," *Front Mar Sci*, vol. 9, 2022.

[43] W. Jo et al., "A low-cost and small usv platform for water quality monitoring," *HardwareX,*, vol. 6, 2019.

[44] V. M. Hernández Guzmán, R. Silva Ortigoza, and R. V. Carrillo Serrano, *Control Automático: Teoría de Diseño, Construcción de Prototipos, Modelado, Identificación y Pruebas Experimentales.* México, 2013.

[45] Y. A. Cengel and J. M. Cimbala, *Mecánica de Fluidos. Fundamentos y Aplicaciones.* MC. Graw Hill, México, 2006.